SZ Interferometry: CBI & Beyond

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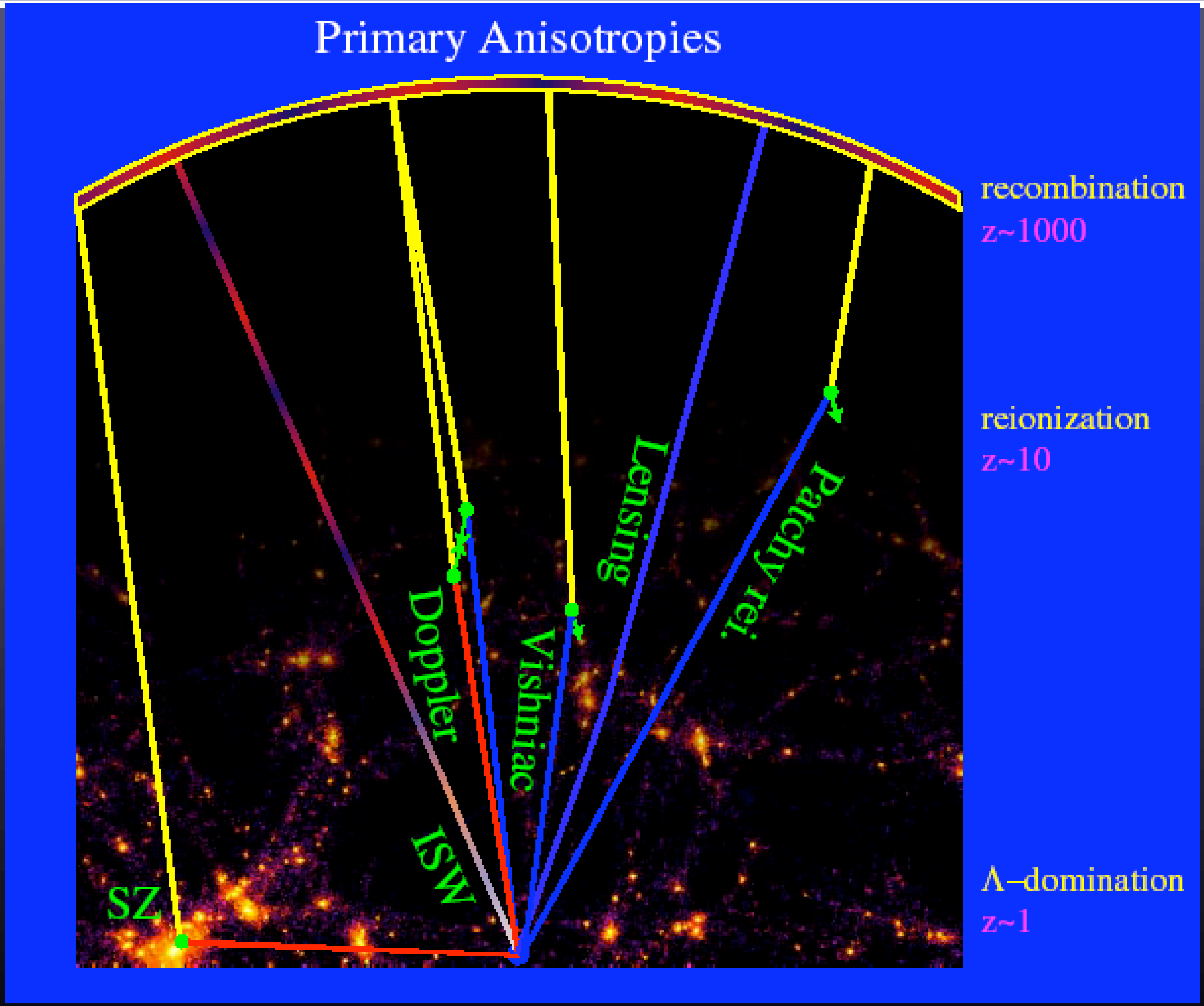
The Sunyaev-Zeldovich Effect

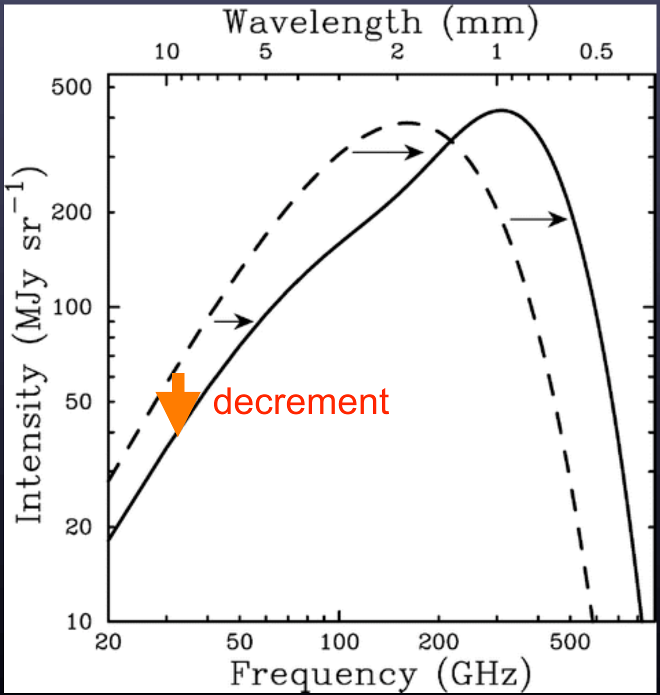
Shadows on the CMB …

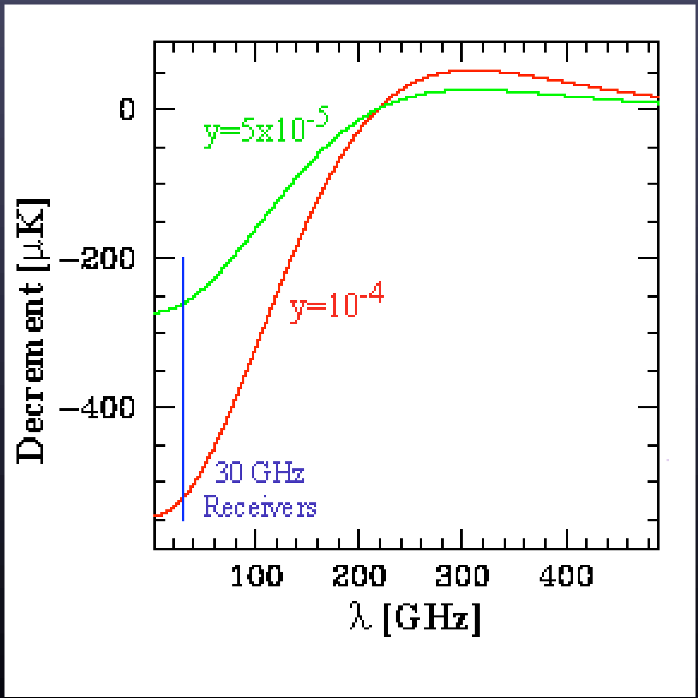


Courtesy Wayne Hu – *http://background.uchicago.edu*

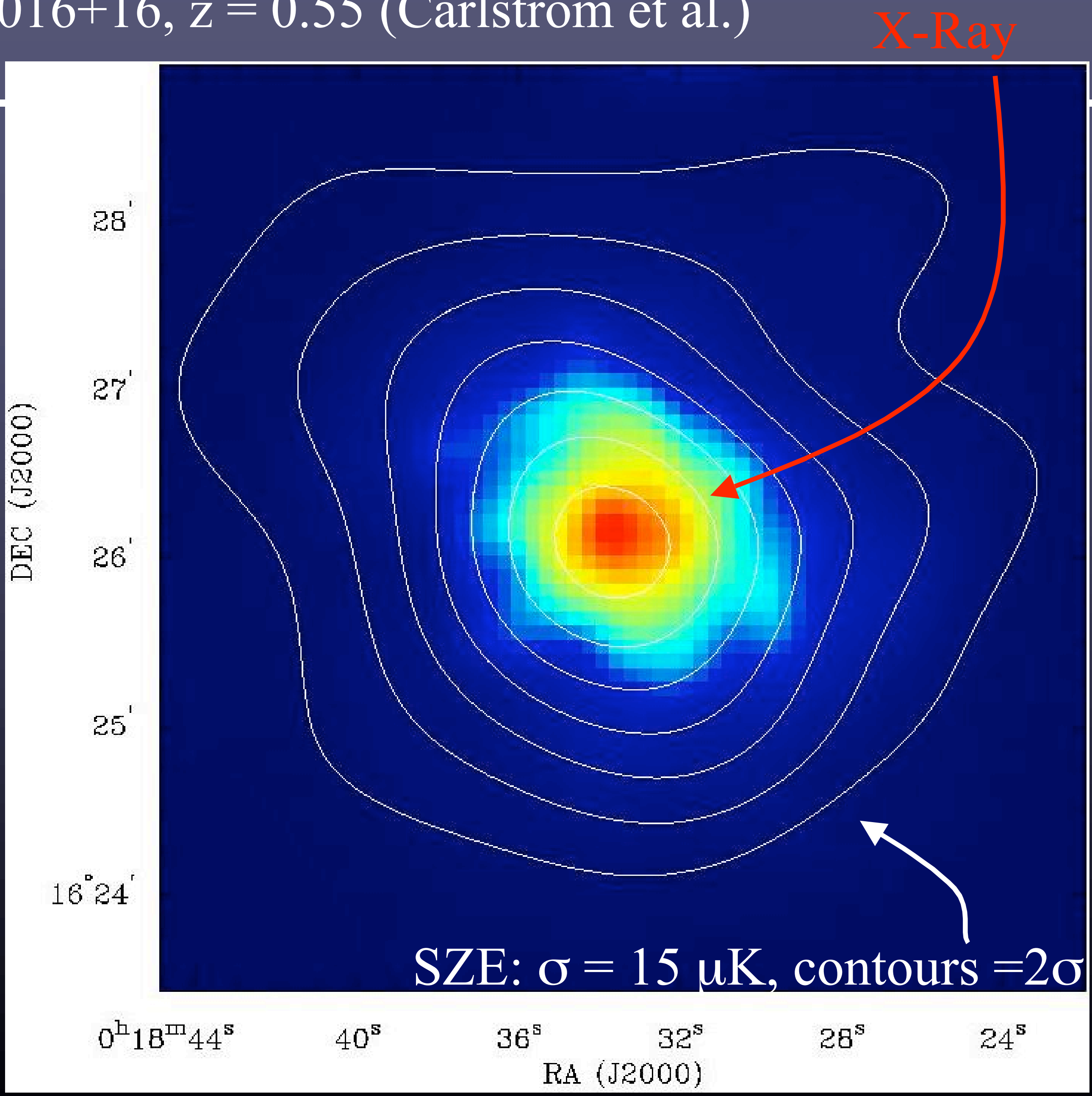
The SZE

- The Sunyaev-Zeldovich Effect
  - Compton upscattering of CMB photons by keV electrons
  - decrement in I below CMB thermal peak (increment above)
  - negative extended sources (absorption against 3K CMB)
  - massive clusters mK, but shallow profile _$^{-1}$ _ -exp(-v)

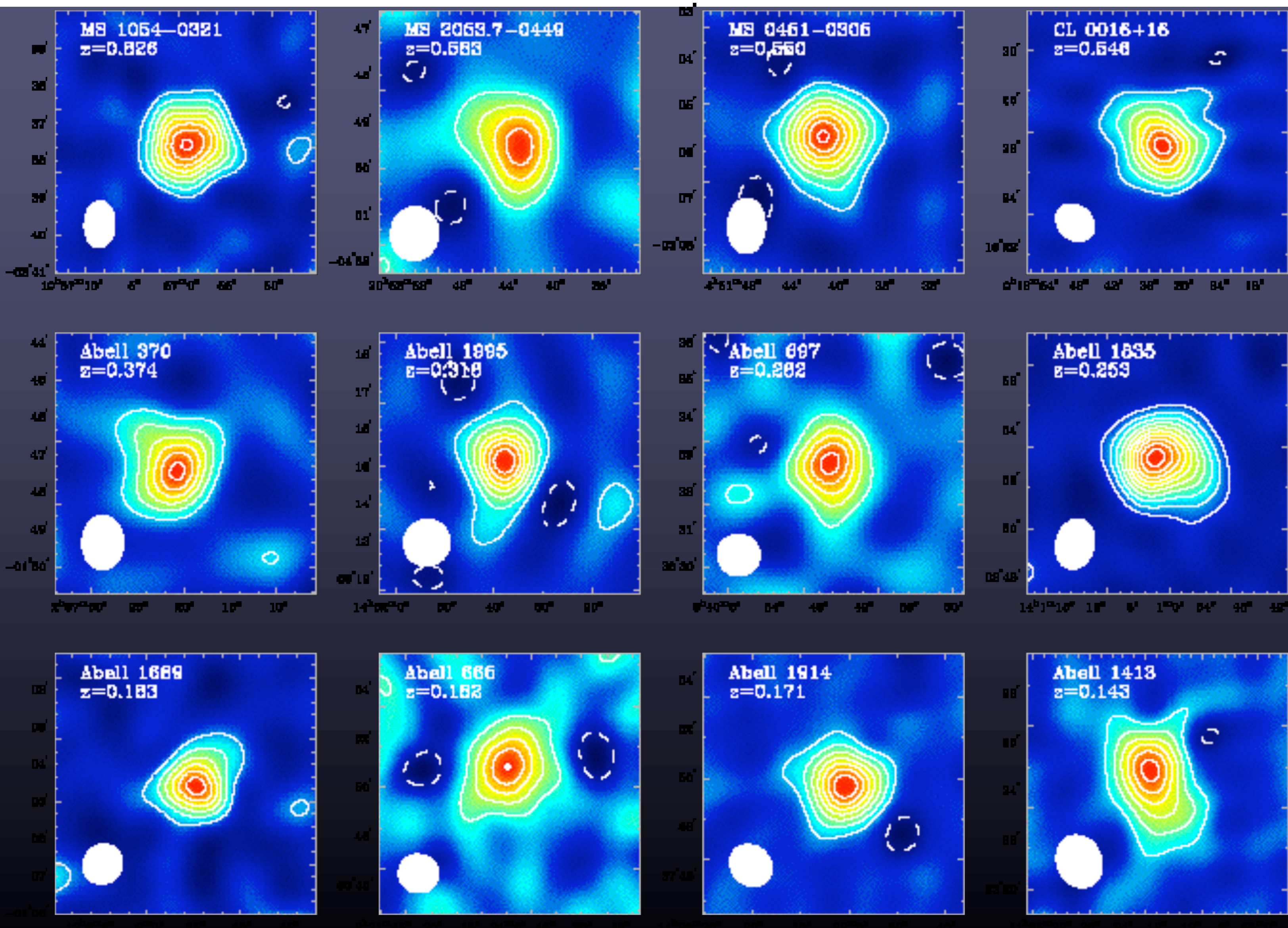




CL 0016+16, z = 0.55 (Carlstrom et al.)



Sample from 60 OVRO/BIMA imaged clusters, 0.07 < z < 1.03



The Cosmic Background Imager

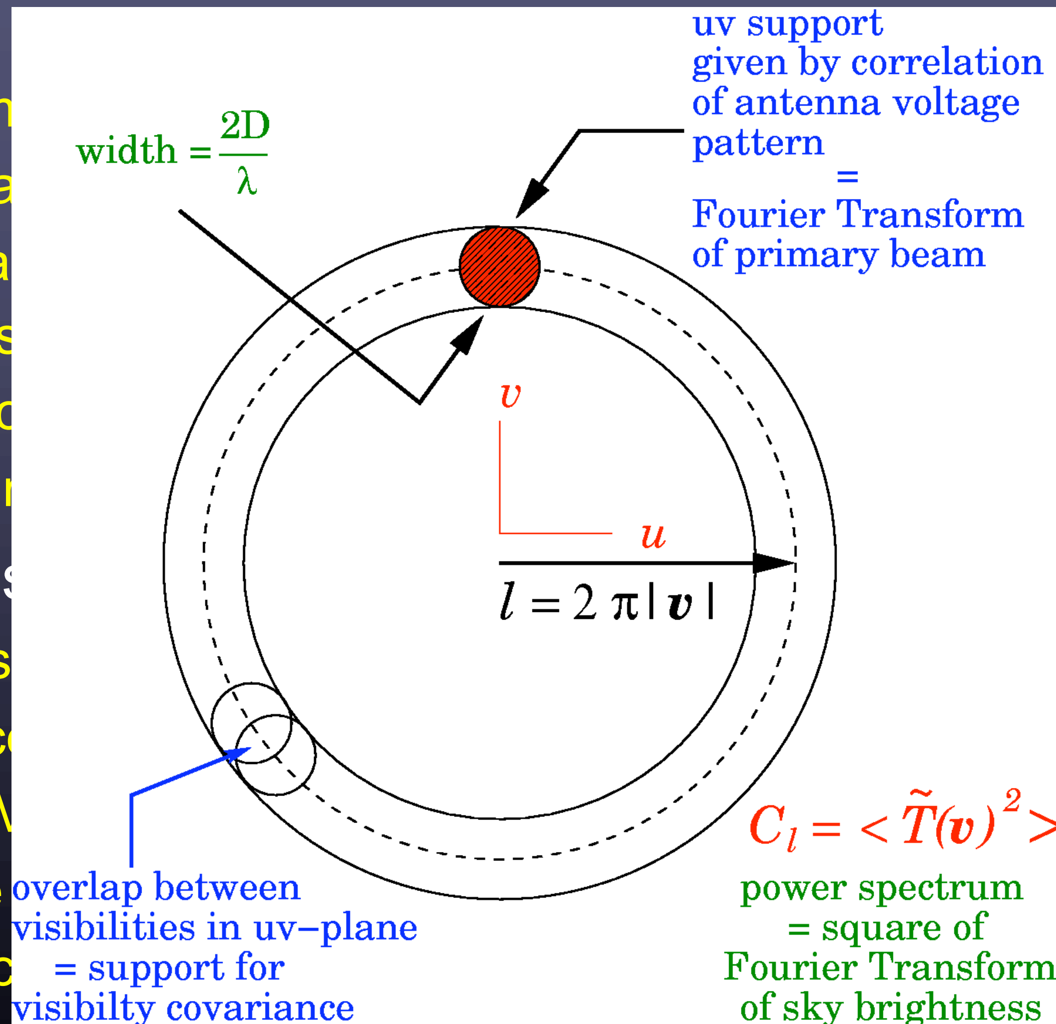
The Instrument

- 13 90-cm Cassegrain antennas
  - 78 baselines
- 6-meter platform
  - Baselines 1m – 5.51m
- 10 1 GHz channels 26-36 GHz
  - HEMT amplifiers (NRAO)
  - Cryogenic 6K, Tsys 20 K
- Single polarization (R or L)
  - Polarizers from U. Chicago
- Analog correlators
  - 780 complex correlators
- Field-of-view 44 arcmin
  - Image noise 4 mJy/bm 900s
- Resolution 4.5 – 10 arcmin

3-Axis mount : rotatable platform

SZ Interferometry: the basics

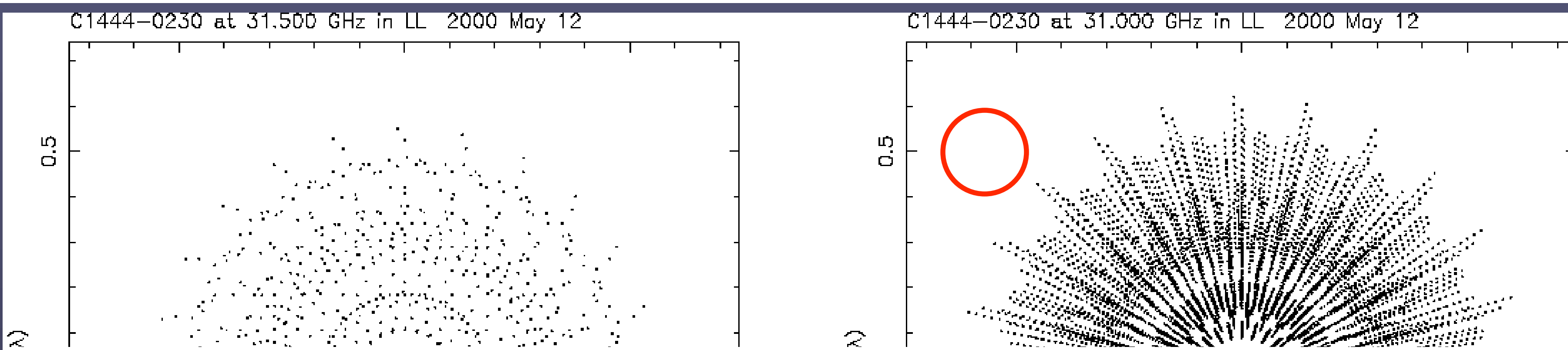
- Interferometry
  - correlate signals fron
  - measures Fourier tra
  - **u**=(*u*,*v*) conjugate va
  - baseline B measures
  - visibility patch 2D/λ c
  - “smeared” by apertur
- Visibilities ⇔ Images
  - Fourier transform vis
  - incomplete Fourier c
  - deconvolution (e.g. M
  - CMB & SZ : analyze
  - point sources : searc

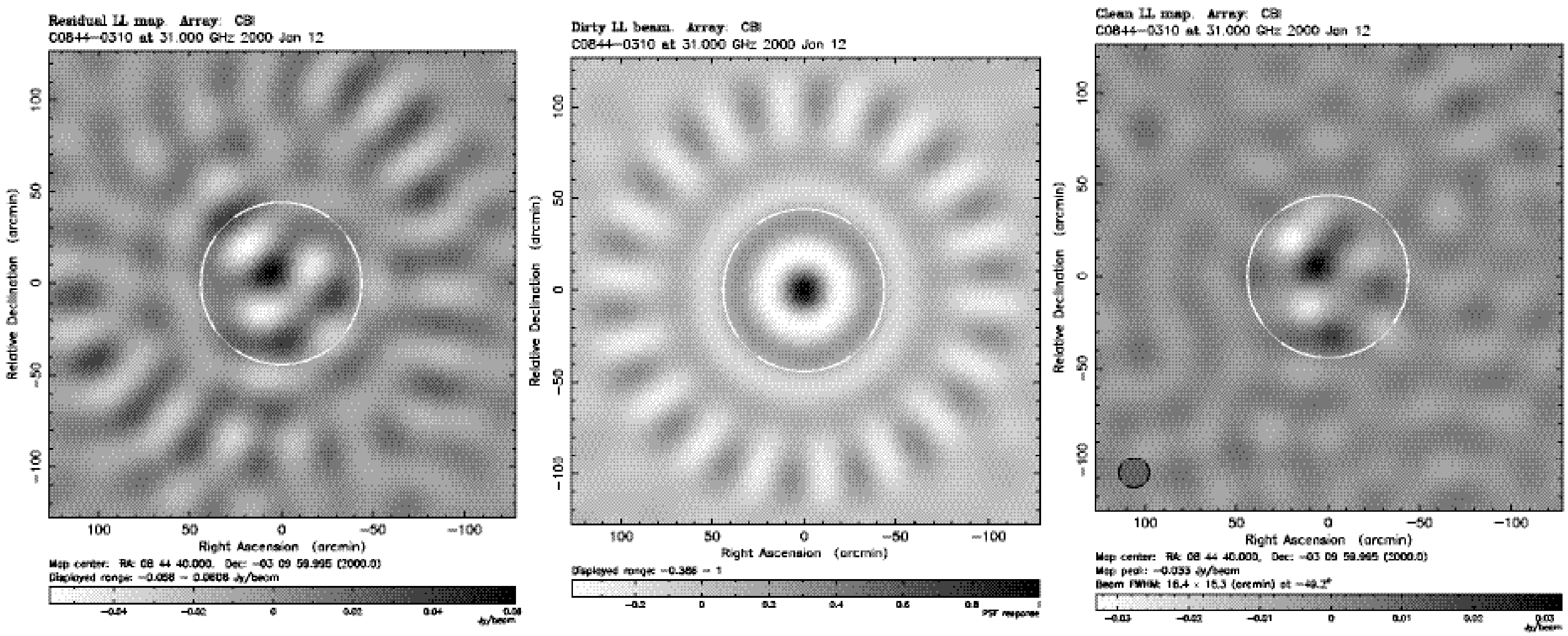


SZ Interferometry: the basics

- Interferometry
  - correlate signals from pairs of antennas = "visibilities"
  - measures Fourier transform of sky brightness
  - **u**=(u,v) conjugate variables ➔ "u-v plane"
  - baseline B measures $l = 2\pi|\mathbf{u}| = 2\pi B/\lambda$
  - visibility patch $2D/\lambda$ compact in Fourier plane
  - "smeared" by aperture size, limits field of view ~D/λ
- Visibilities ⇔ Images
  - Fourier transform visibilities to make image
  - incomplete Fourier coverage ➔ PSF ("dirty beam")
  - deconvolution (e.g. MEM or CLEAN)
  - CMB & SZ : analyze in Fourier domain directly
  - point sources : search & destroy in image plane

CBI Beam and *uv* coverage





The CBI SZE Program

The CBI S

- led by Patric
  2003)
- drawn from
  Grandi et al
- f $_{0.1\text{-}2.4\text{keV}}$ > 1
- z < 0.1
- L $_{0.1\text{-}2.4\text{keV}}$ >
- declination -
- 24 clusters a
- primary sam
- detailed in U
  Pearson (20

Cluster	z	$L_{0.1-2.4\text{keV}}$ $(h^{-2}10^{44}\text{erg/s})^a$	*ROSAT*	*ASCA*	*XMM-Newton*	*Chandra*
A2029	0.773	3.84	P	y	G	S
A478	0.0881	3.24	P	y	G	S
A401	0.0737	2.47	P	y	G	I
A3667[S]	0.0556	2.32	P	y	G	I
A85	0555	2.15	P	y	B	I
A3827[S]	0.0984	1.95	H		B	
A3571	0.0391	1.94	P	y	B	
A3266[S]	0.0589	1.89	P	y	G	I
A1651	0.0844	1.85	P	y		I
A754	0.0542	1.80	P	y	G	I
A3112[S]	0.0750	1.79	P	y	G	S
A399	0.0724	1.61	P	y	G	I
A1650	0.0845	1.61	P	y	B	
A2597	0.0852	1.48	P	y	G	S
A3558	0.0480	1.46	P	y	G	S
A3695	0.0894	1.44	H			
PKS1550-140	0.0970	1.42				
A3158[S]	0.0597	1.37	P	y		I
A3921[S]	0.0936	1.32	P	y	G	
Z5029	0.0750	1.32				
A780	0.0539	1.23	P	y	G	I,S
A3911[S]	0.0965	1.23	P			
A2420	0.0846	1.16				
A4010	0.0957	1.16				

[a] XBACs and REFLEX assume $h = 0.5$. Here we convert their luminosities to units of $h = 1$.
[S] Southern Source, not accessible with VLA or OVRO 40-m
ROSAT : P = Public PSPC, H = Public HRI only
ASCA : y = public data available
XMM-Newton : G = Guaranteed Time Target, B = General Observer Target
Chandra : I = ACIS-I, S = ACIS-S

Subsample 7 clusters

Cluster	R.A. (J2000)	Decl. (J2000)	L&T offsets (min)	Hours Observed (L+M+T)	rms noise (mJy/beam)	Beam FWHM
A85	00:41:48.7	−09:19:04.8	±16.5	16.6	1.8	5.3′
A399	02:57:49.7	+13:03:10.8	±12.5	15.6	2.0	5.4′
A401	02:58:56.9	+13:34:22.8	±12.5	15.7	2.0	5.4′
A478	04:13:26.2	+10:27:57.6	±10	12.2	2.4	5.2′
A754	09:09:01.4	-09:39:18.0	±9	16.0	1.9	5.4′
A1651	12:59:24.0	-04:11:20.4	±11	16.3	2.0	4.9′
A2597	23:25:16.6	-12:07:26.4	±15.5	11.6	2.3	5.5′

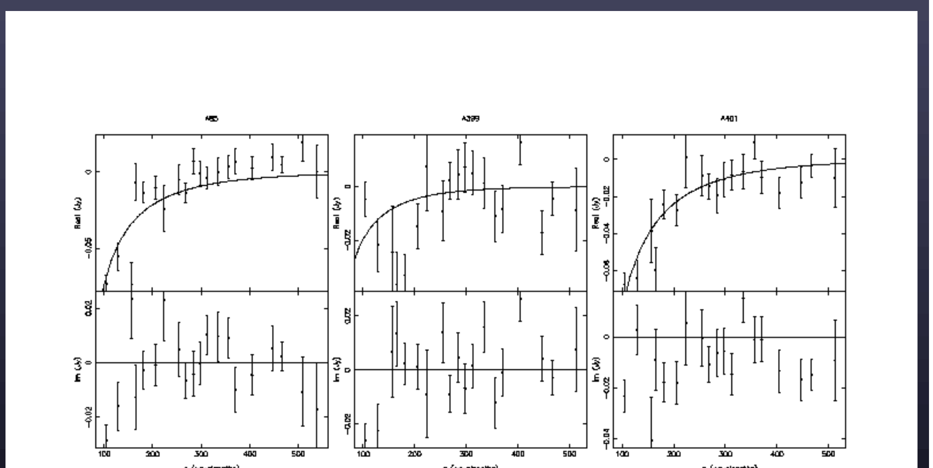
Cluster	θ_0 (arcm)
A85	2.04±0.52
A399	4.33±0.45
A401	2.26±0.41
A478	1.00±0.15
A754	5.50±1.10
A1651	2.16±0.36
A2597	0.49±0.03

Cluster	*ASCA* White (keV)	MFSV (keV)	*ASCA* Avg (keV)	*BeppoSAX* DM2002 (keV)	*BeppoSAX* & *ASCA* average	error in $h^{-1/2}$	Cooling Flow or Single Compon
A85	6.74±0.50	6.9±0.2	6.8±0.5	6.83±0.15	6.8±0.2	±2.9%	CF
A399	6.80±0.17	7.0±0.2	6.9±0.2			±2.9%	SC
A401	8.68±0.17	8.0±0.2	8.3±0.4			±4.8%	SC
A478	$7.42^{+0.71}_{-0.54}$	$8.4^{+0.5}_{-0.8}$	7.9±0.8			±10.1%	CF
A754	9.83±0.27	$9.5^{+0.4}_{-0.2}$	9.7±0.3	$9.42^{+0.16}_{-0.17}$	9.5±0.2	±2.1%	SC
A1651	$6.21^{+0.18}_{-0.17}$	6.1±0.2	6.2±0.2			±6.3%	SC
A2597	$3.91^{+0.27}_{-0.22}$	$4.4^{+0.2}_{-0.4}$	4.2±0.4			±9.5%	CF

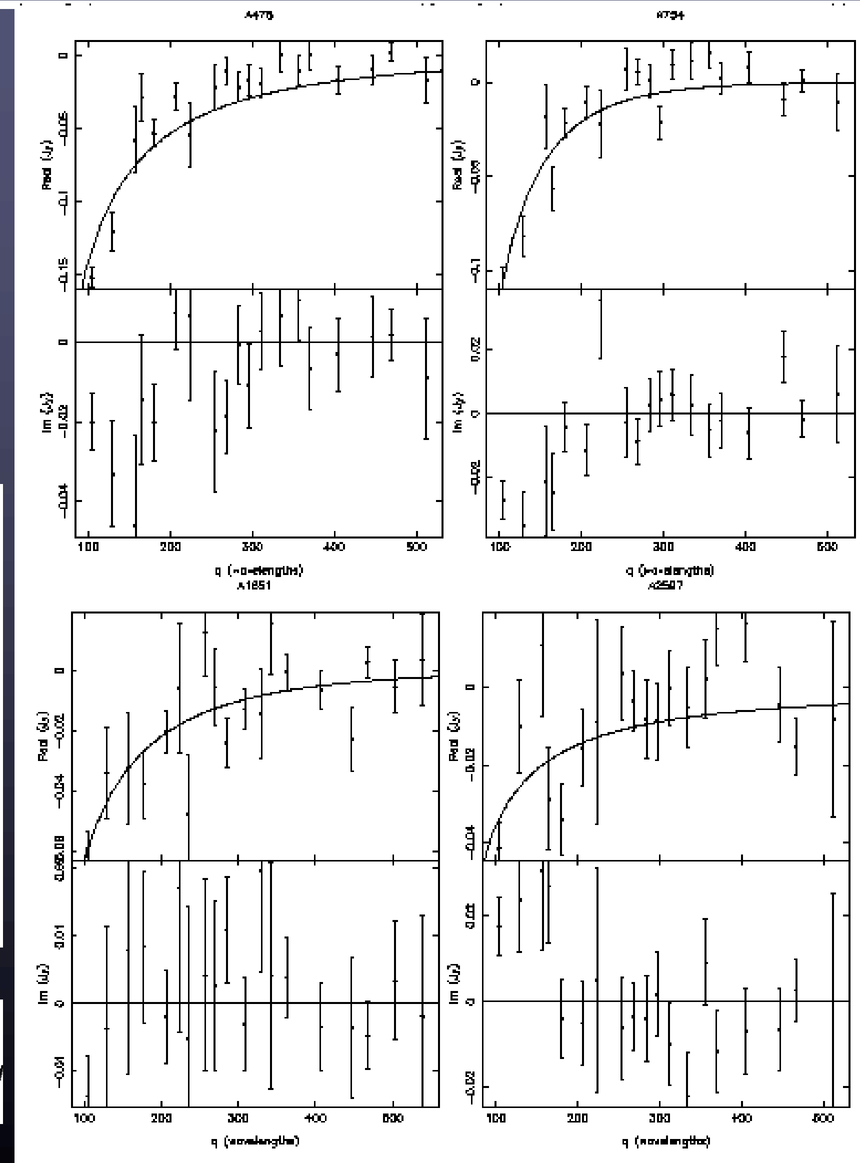
- covers a range of luminosities and cluster types

CBI SZE visibility function

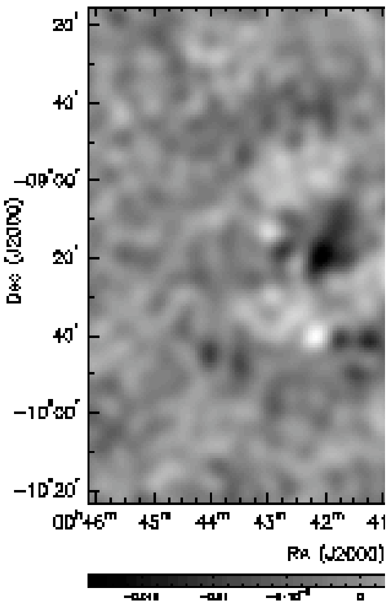
- Xray: _$^{-3}$ (β ~ 2/3)
- SZE: _$^{-1}$ _ -exp(-v)
- dominated by shortest baselines



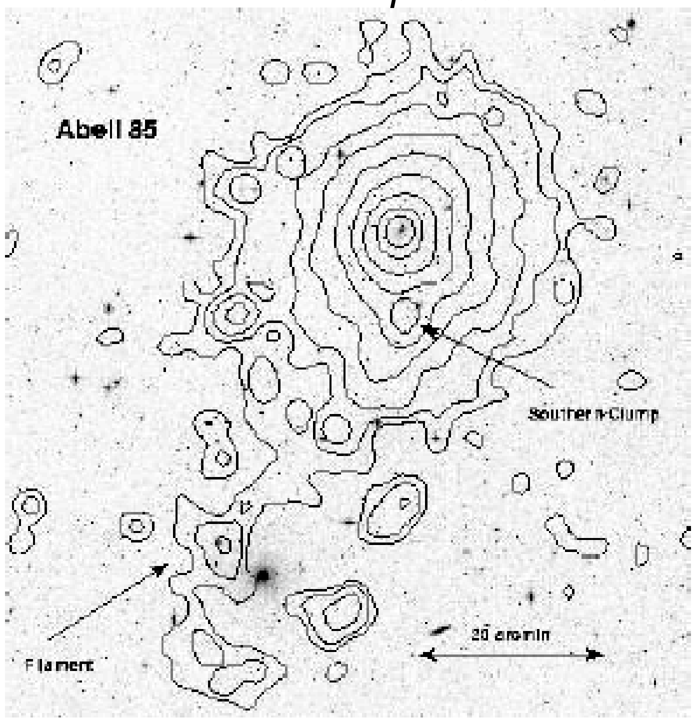
$$V(u,v) = I_0 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} B(\theta) \left(1 + \frac{\theta^2}{\theta_0^2}\right)^{-\frac{3}{2}\beta+\frac{1}{2}} e^{2\pi i(ux+vy)}\, dx\, dy$$



A85



Forman et al. astro-ph/0301476



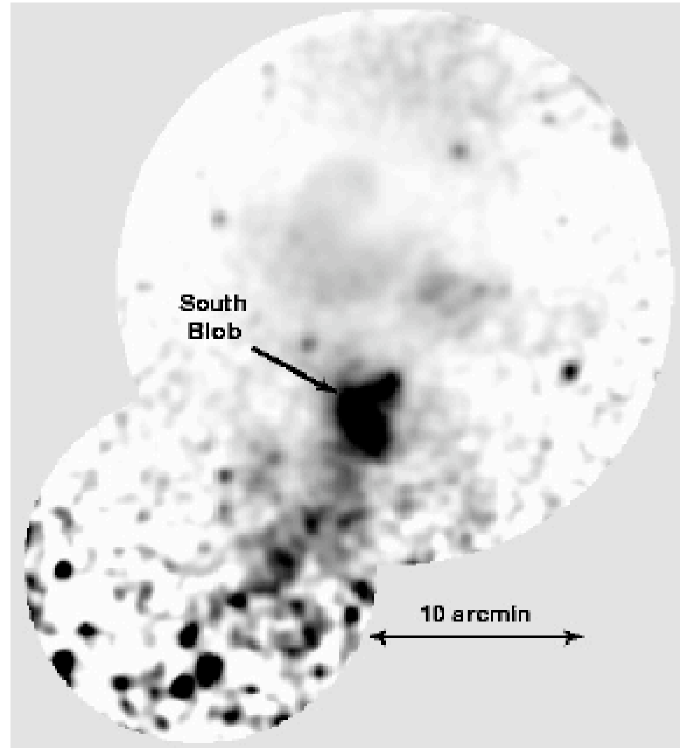
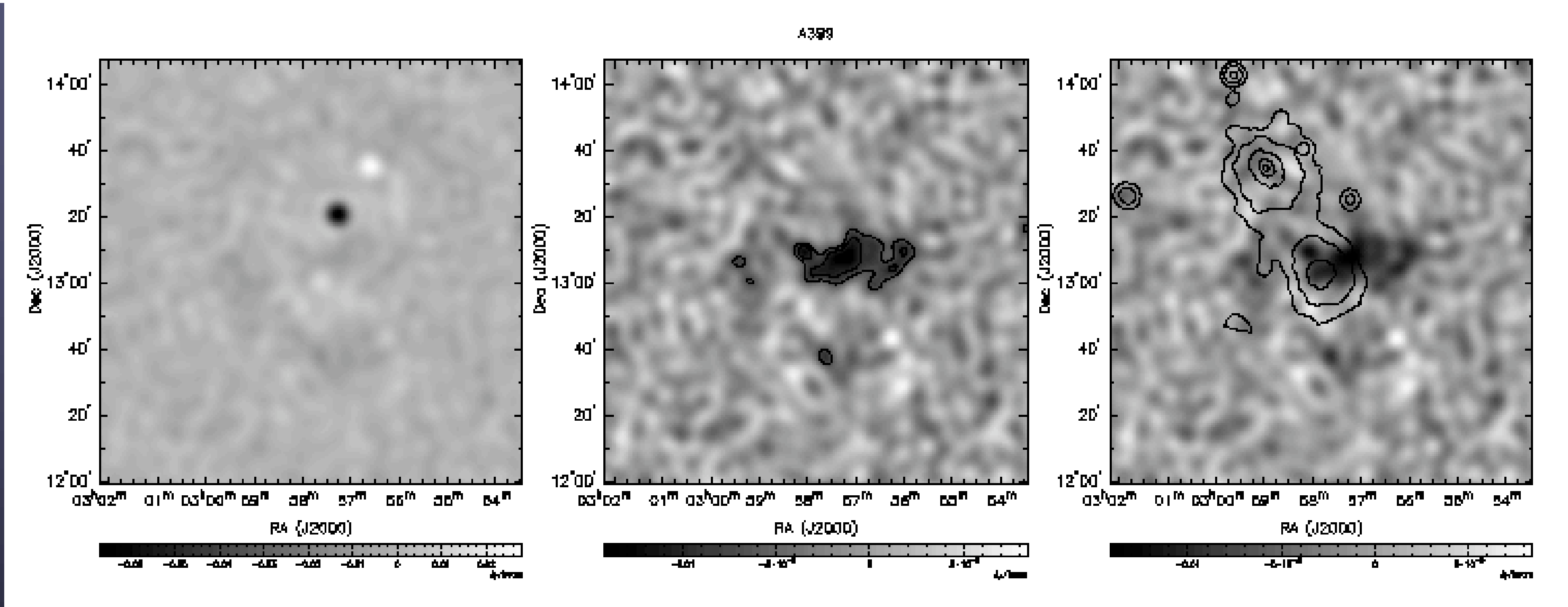


Figure 1. ROSAT and XMM-Newton observations of A85 (**a**) ROSAT PSPC iso-intensity contours (0.4-2.0 keV) are shown superposed on an optical image (adapted from Durret et al. 1998). A filamentary structure extends to the southeast. (**b**) The XMM-Newton MOS image shows the inner portion of the filament extending southeast from the South Blob (Southern Clump) (Durret et al. 2003).

(left) Raw CBI Ima

- A85 – cl
  activity,

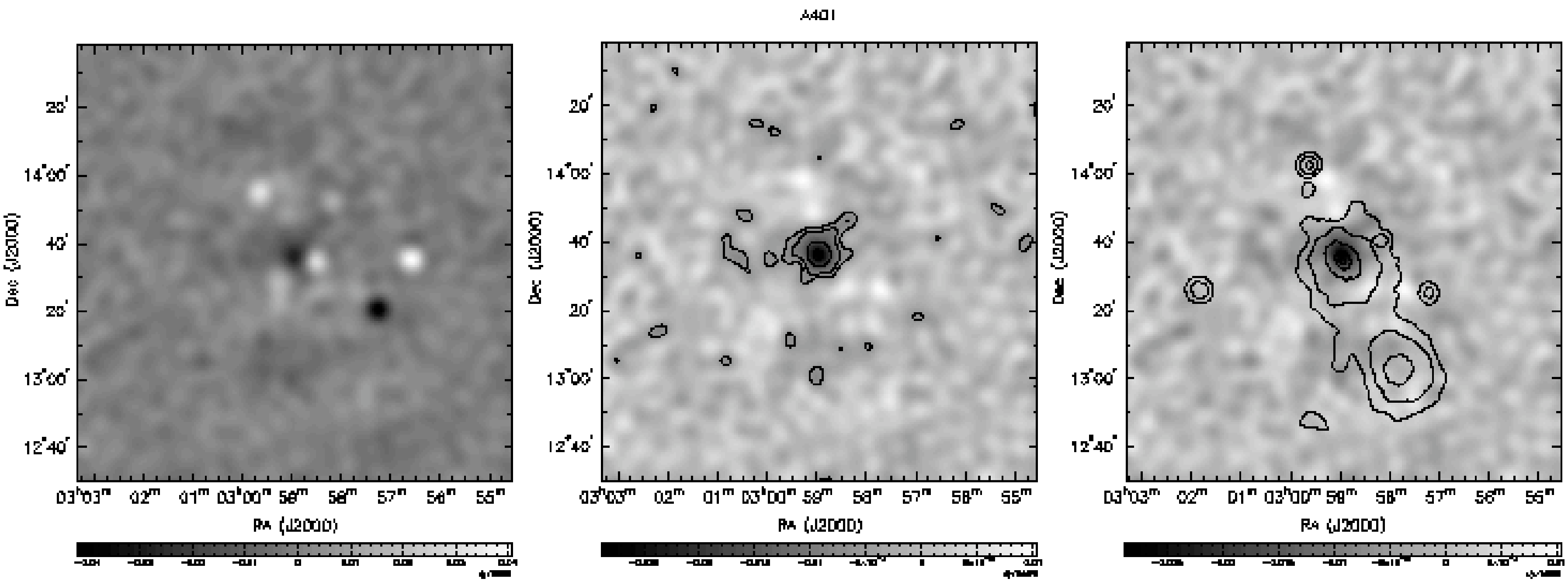
A399



(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

- A399 – pair with A401

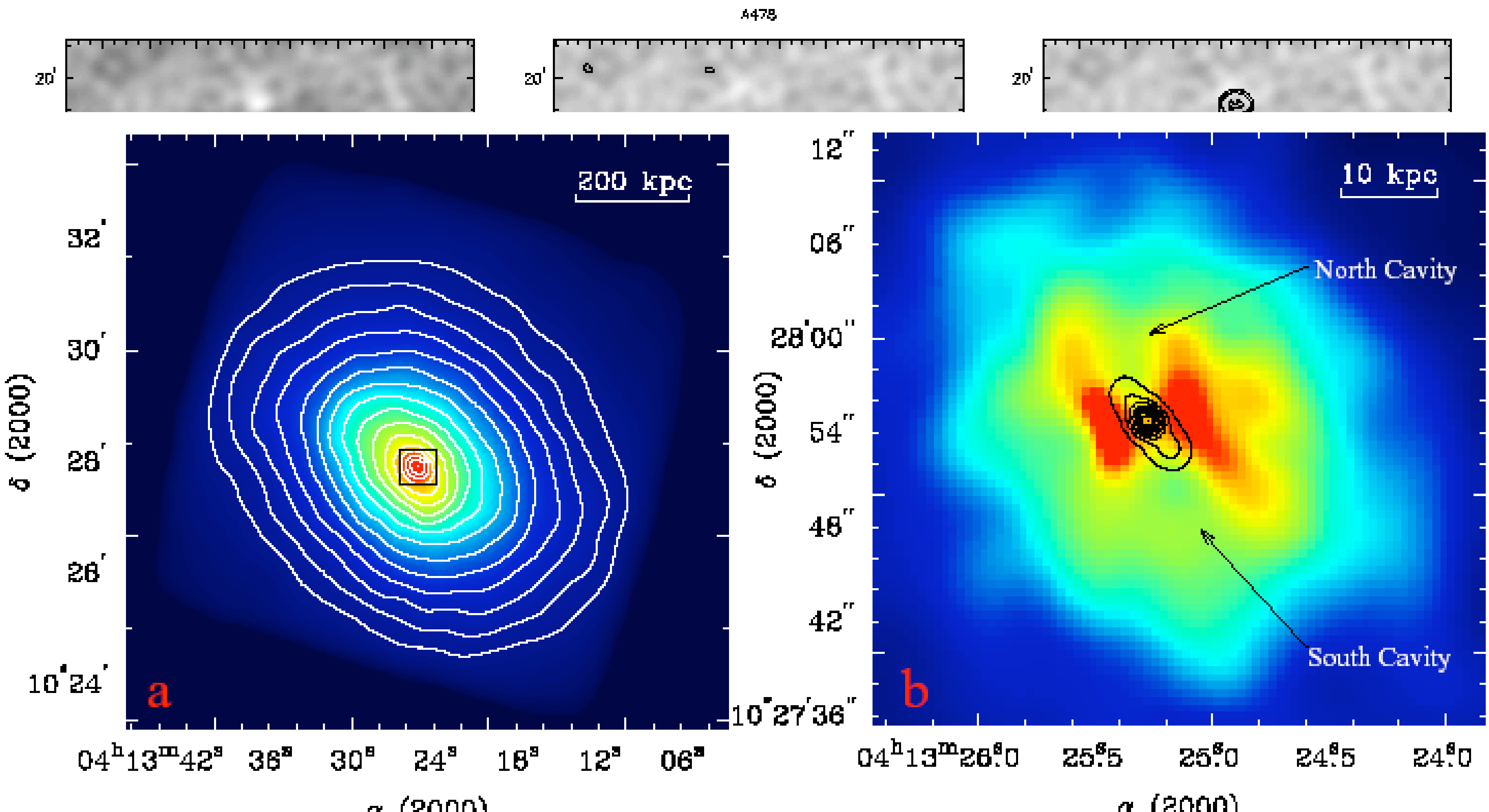
A401



(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

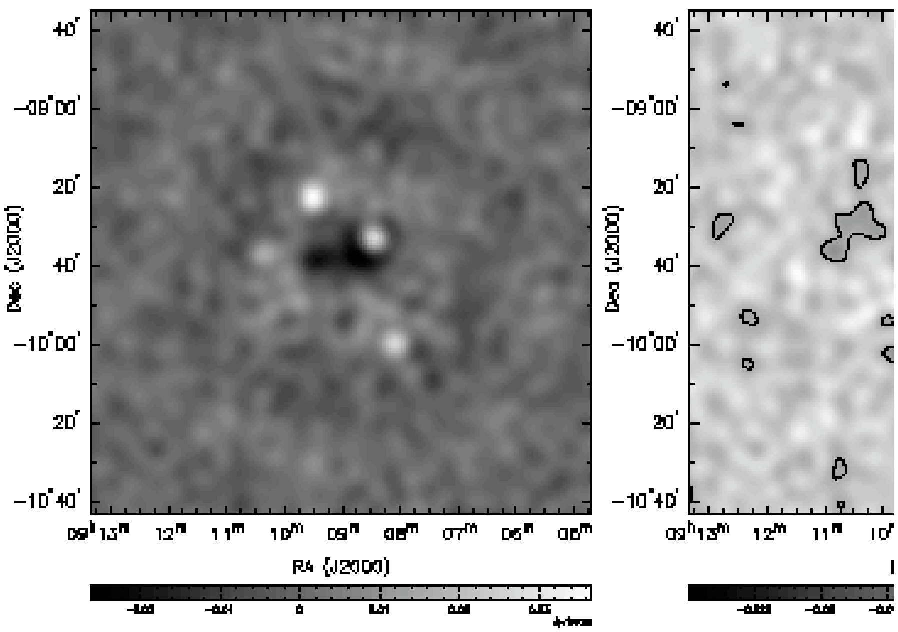
- A401 – pair with A399, likely interacting now or in past, cooling flow disrupted?

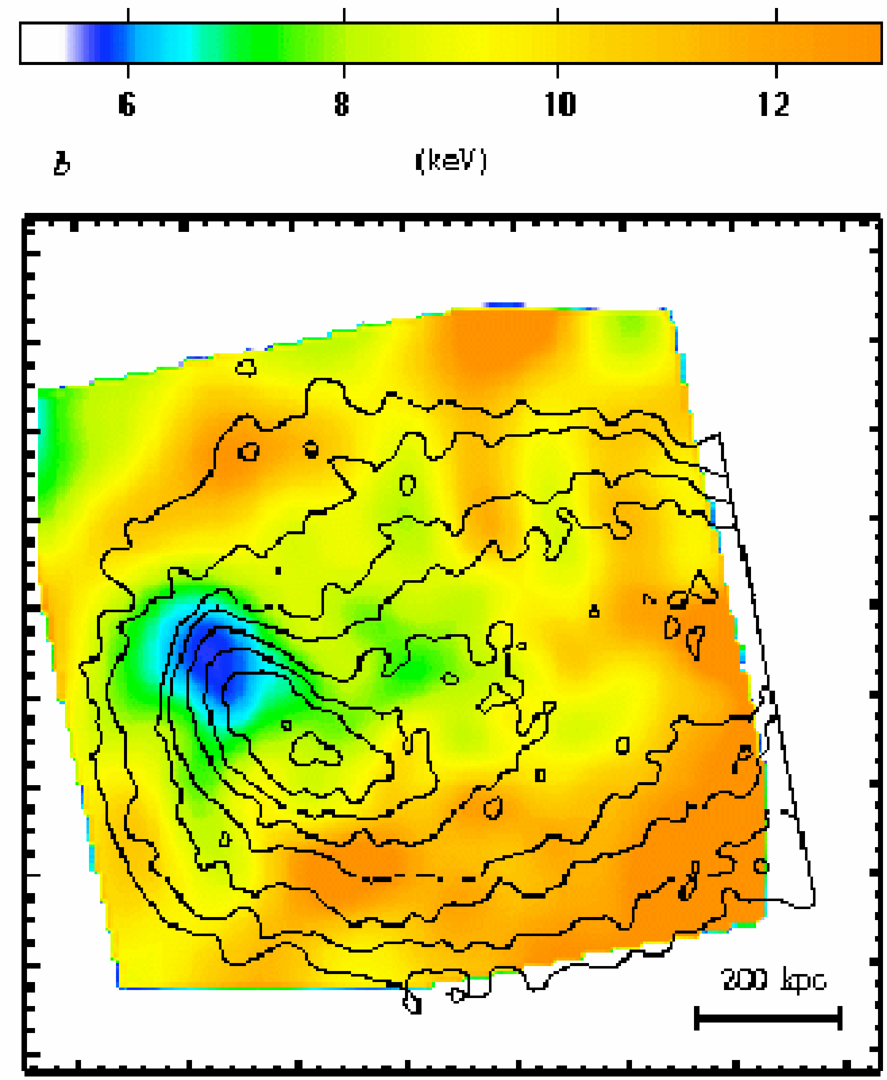
A478



Chandra: Sun et al. astro-ph/0210054 *(inner region + 1.4 GHz radio)*

A754



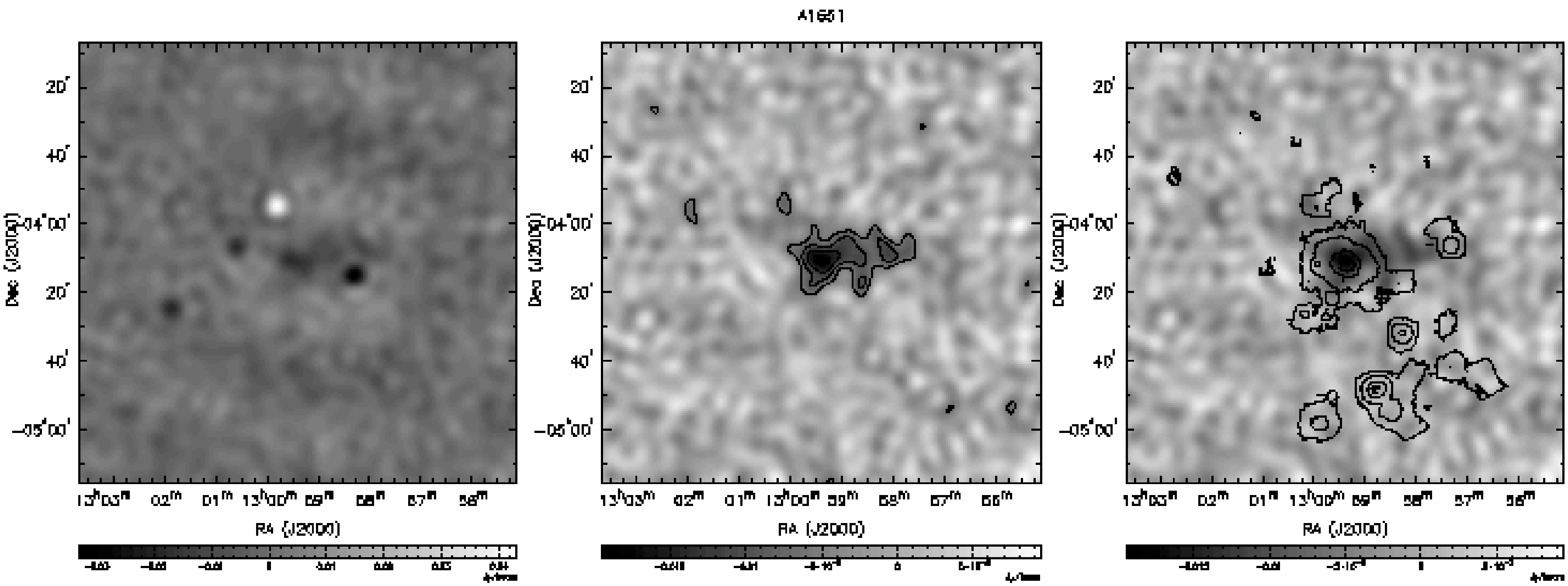


Chandra: Govoni et al. astro-ph/0401421

(left) Raw CBI Image (center) CLEAN so

- A754 – “prototypical” violent m

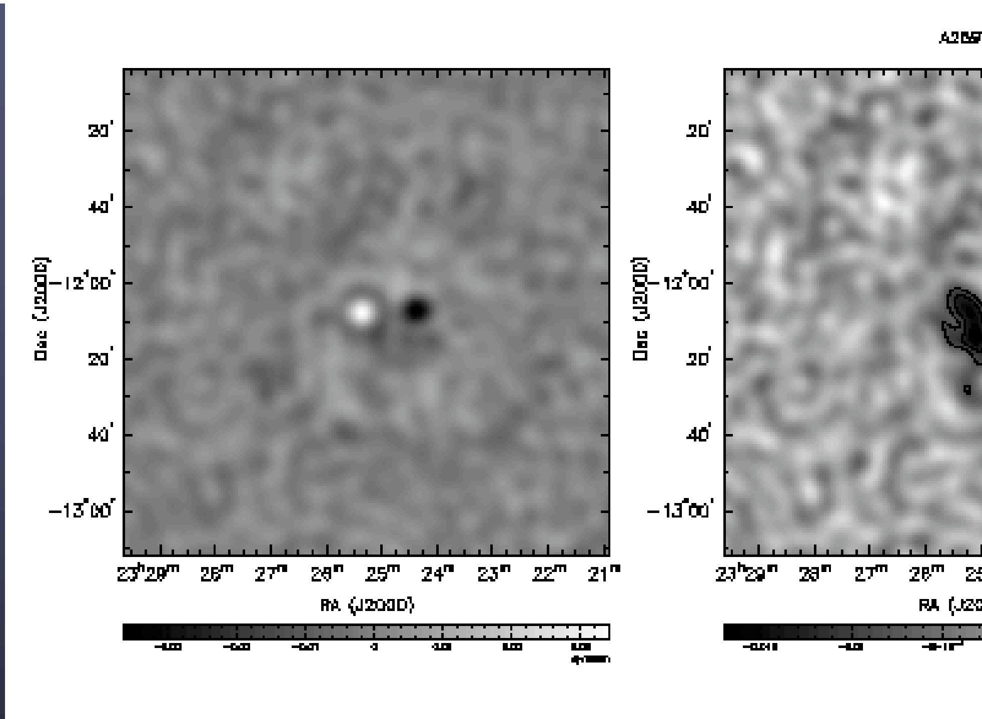
A1651

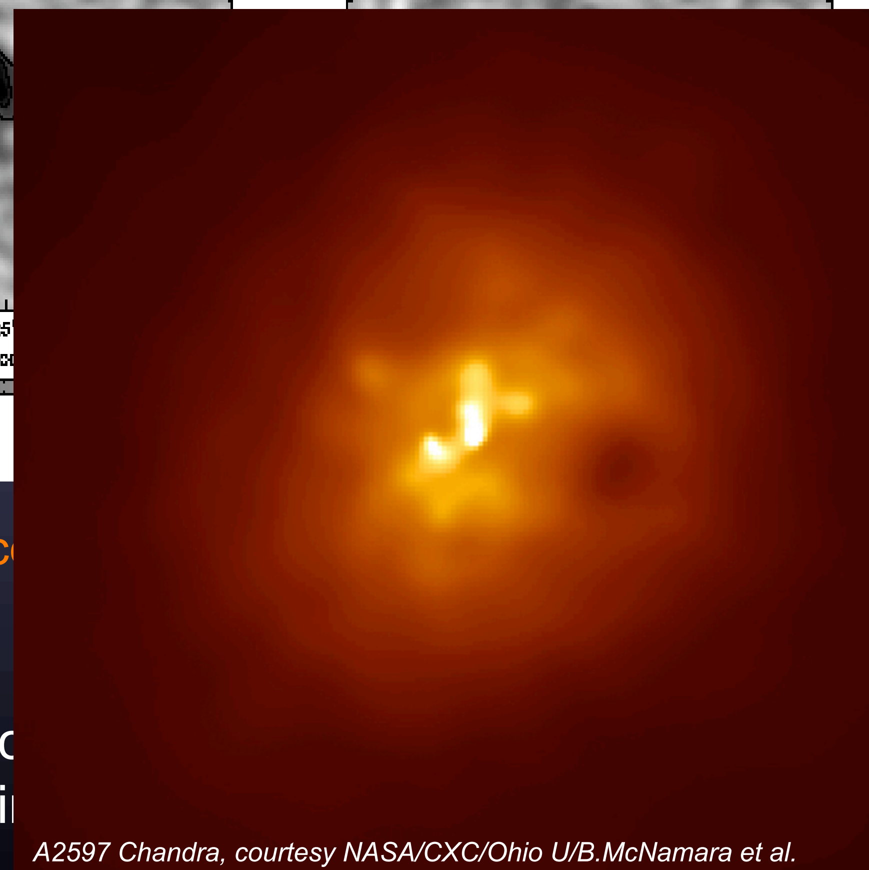


(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

- A1651 – dynamically relaxed cD cluster, unremarkable

A2597





A2597 Chandra, courtesy NASA/CXC/Ohio U/B.McNamara et al.

(left) Raw CBI Image (center) CLEAN sourc

- A2597 – regular cD cluster with c
raw image) with X-ray shadows i

SZE vs. X-rays

- gas density profiles: $$n_e(r) = n_{e0}\left(1+\frac{r^2}{r_0^2}\right)^{-3\beta/2}$$
- X-ray surface brightness: $$b_X(E) = \frac{1}{4\pi(1+z)^3}\int n_e^2(r)\Lambda(E,T_e)\,dl$$
- SZE surface brightness: $$\Delta I_{\rm SZE} \propto T_e \int n_e\,dl$$
- dependence on parameters:

$$b_X \propto n_{e0}^2\theta_0 D_A\left(1+\frac{\theta^2}{\theta_0^2}\right)^{-3\beta+1/2}$$

$$\Delta I_{\rm SZE} \propto T_e n_{e0}\theta_0 D_A\left(1+\frac{\theta^2}{\theta_0^2}\right)^{-\frac{3}{2}\beta+\frac{1}{2}}$$

- $D_A \sim h^{-1}$ $n_{e0} \sim h^{1/2}$ _ $\Delta I_{SZE} \sim h^{-1/2}$

Results

- unweighted $H_0 = 67\ ^{+30}_{-18}\ ^{+13}_{-6}$ km/s/Mpc
- weighted $H_0 = 75\ ^{+23}_{-16}\ ^{+15}_{-7}$ km/s/Mpc
- uncertainties dominated by CMB confusion
- based on older X-ray data…

Cluster	Corrected $h^{-1/2}$ w/ total random error	ΔT_0 μK	Compton-y_0 $(\times 10^{-4})$
A85	1.23±0.40	-580±190	1.13±0.37
A399	0.24±0.42	-80±130	0.15 ±0.26
A401	1.03±0.29	-620±170	1.20 ±0.34
A478	1.76±0.34	-1800±350	3.49±0.68
A754	1.09±0.31	-560±160	1.09±0.31
A1651	1.42±0.47	-520±170	1.00±0.33
A2597	1.74±1.10	-750±670	1.43±1.28
mean ± sd =	1.22±0.52		
(probability=21%)	$\frac{\chi^2}{\nu} = 1.47$ for 6 dof		
unweighted sample average: $h^{-1/2}$ =	1.22±0.20		
→	$h = 0.67^{+0.30}_{-0.18}$		
weighted sample average: $h^{-1/2}$ =	1.16±0.14		
→	$h = 0.75^{+0.23}_{-0.16}$		

Gastrophysics?

- “mergers” A85, A399/401, A754
  - A401 & A754 somewhat low, A399 very low (but uncertain)
- “cooling cores” A85, A478, A2597
  - A478 high, A2597 very high (but uncertain)

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weighted sample average: $h^{-1/2}$ =	1.16±0.14		
→	$h = 0.75^{+0.23}_{-0.16}$		

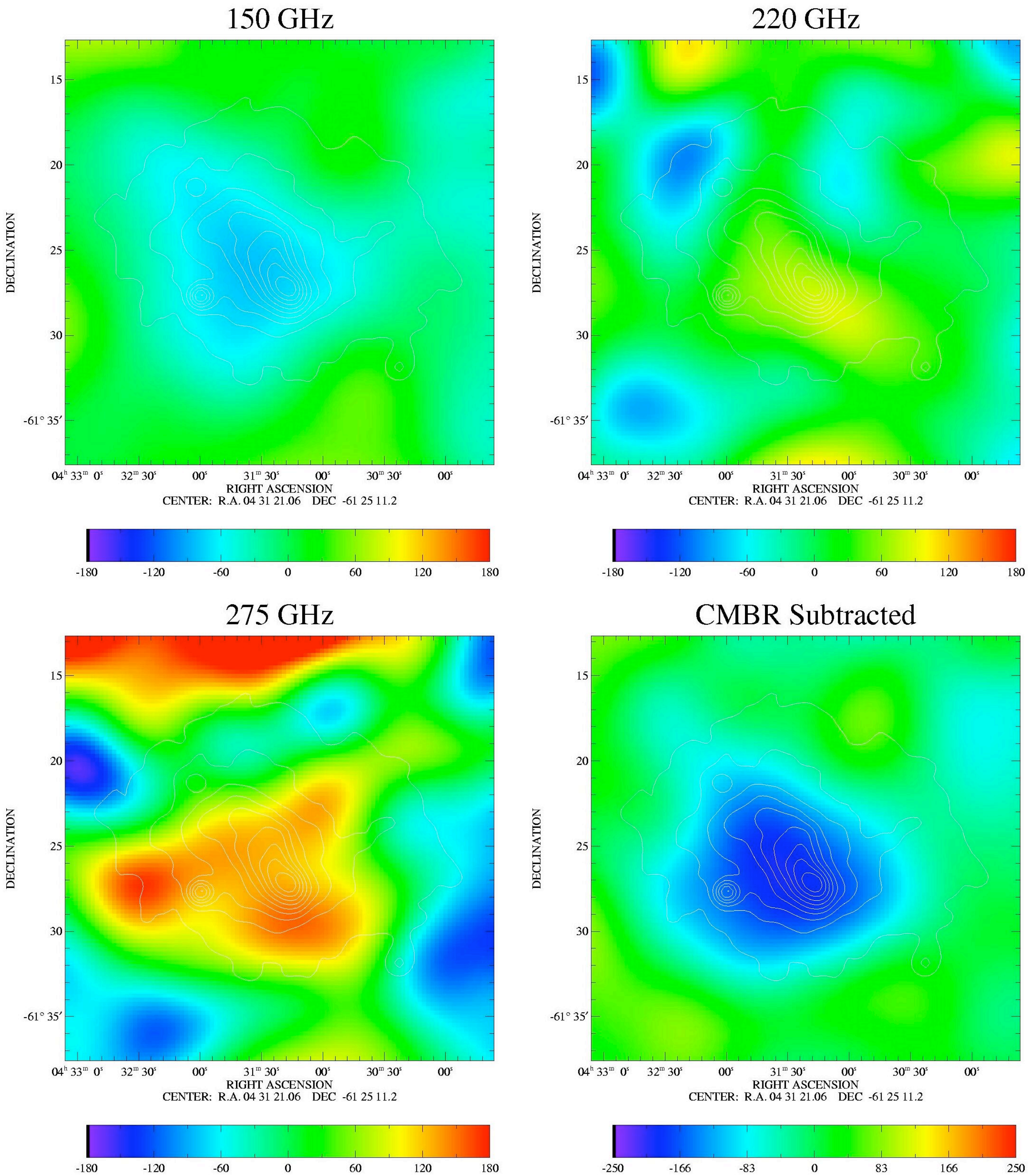
Error Budget

- CMB anisotropies – the dominant uncertainty
- density model – β models, some bias correction needed
- temperature profiles – assume isothermal, investigate deviations
- radio point sources – residuals small after using counts
- cluster asphericity – < 4%, could be worse in individual clusters
- clumpy gas distribution – $\langle n_e^2 \rangle / \langle n_e \rangle^2$ bias, substructure?
- peculiar velocities – no bias, 0.04% for even 1000 km/s!
- non-thermal Comptonization – unknown, model dependent

Cluster	CMB error	X-ray mod bias	pt src bias	T_e error	V_{pec} error	CMB+Ther+ptso error
A85	±0.36	1.01	+0.00	0.03	0.05	±0.38
A399	±0.42	1.01	+0.02	0.03	0.05	±0.42
A401	±0.27	1.01	+0.03	0.05	0.04	±0.27
A478	±0.25	1.00	+0.00	0.10	0.04	±0.25
A754	±0.26	1.04	+0.02	0.02	0.04	±0.29
A1651	±0.43	1.00	+0.00	0.06	0.06	±0.44
A2597	±1.06	1.00	+0.01	0.09	0.08	±1.07

And the upshot is…

- Sample average H_0 consistent with canonical value
  - uncertainties dominated by CMB, then astrophysics
  - is there significant scatter among clusters?
  - finish the full sample!
- Gastrophysics not cosmology
  - turn it around – what does scatter say about clusters?
  - need to use latest Chandra & XMM-Newton data!
  - shocks : probably not in pressure equilibrium
  - bubbles : how far out of pressure equilibrium???
- What about the pesky CMB?
  - more distant clusters better, CMB less on smaller scales
  - substructure measurements easier also (CMB resolved out)
  - spectrum: would like to measure CMB at SZE null (2mm)



First ACBAR Cluster Image: A3266

z=.0545

T_x=6.2 keV

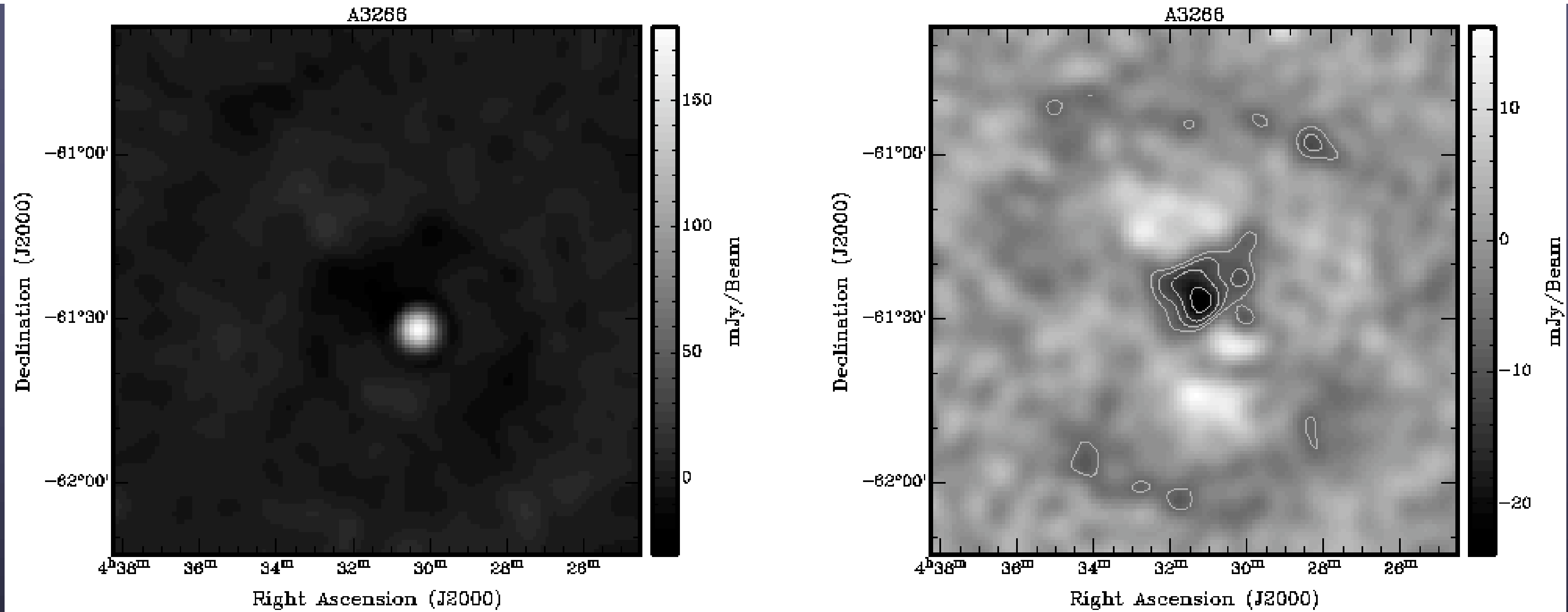
L_x=9.5x10^{44}

Requires Multi-frequency Data to Subtract CMB

Latest results – A3266 & A3558

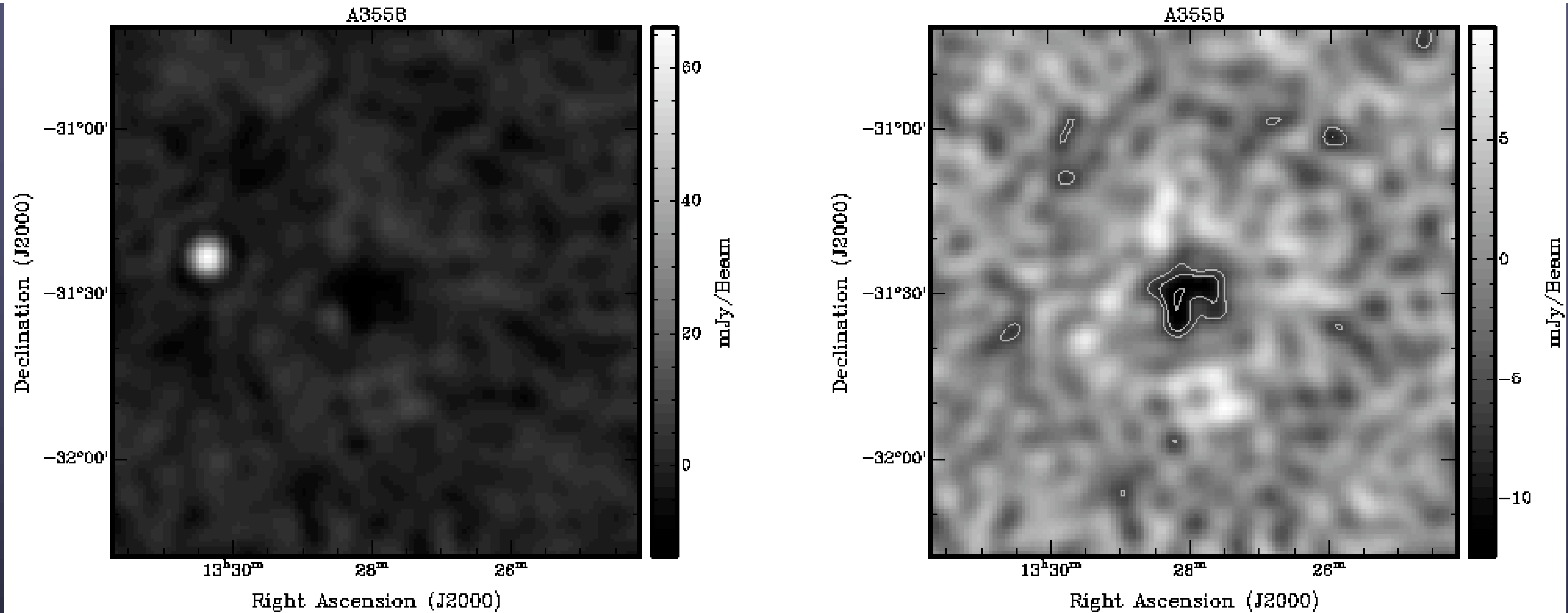
- Adrienne Stilp (U.Wisc.) – NRAO REU 2004 project
- Trial MCMC analysis of CBI data plus X-ray models
  - method similar to Bonamente et al. 2004
  - fit n_0, T_0, β, θ_c, D_A (spherical isothermal models)
  - X-ray models from ROSAT (Mason & Myers 2000) + ASCA
  - $H_0 = 65 \pm 14$ (1σ)
  - does not include effect of CMB (dominant uncertainty)
- Next – full analysis
  - deal with CMB and sources
  - use Chandra and XMM-Newton data
  - some additional CBI compact configuration data
- Other clusters (A3667, A3827,…)
  - have ATCA 18 GHz images for point sources

Latest results – A3266



A3266 - before & after source subtraction

Latest results – A3558

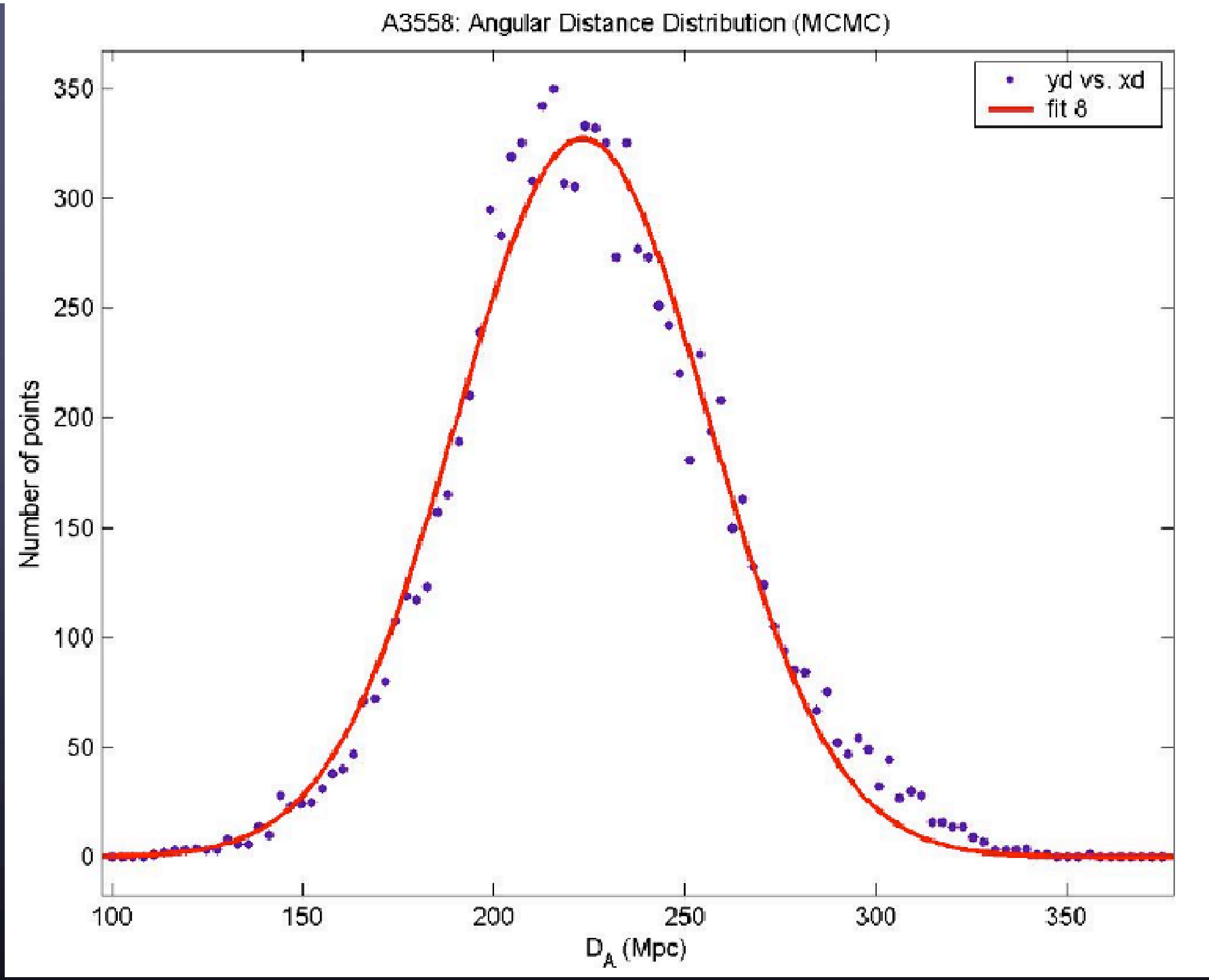


A3558 – before & after source subtraction

In Shapley supercluster (w/A3571)

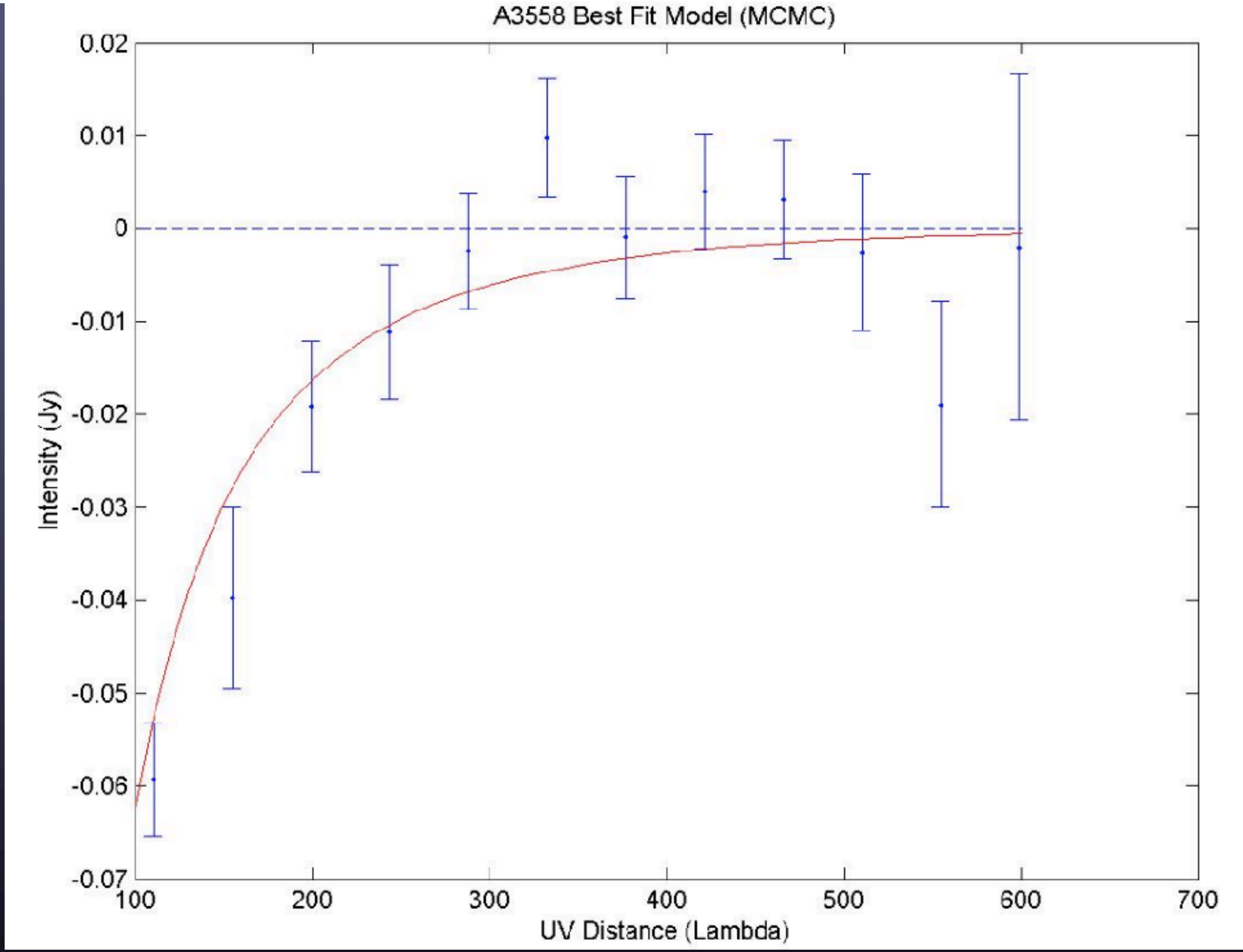
- CBI currently surveying SSC (Oxford group)

Latest results – A3558



- A3558 – MCMC distribution of D_A (no CMB)

Latest results – A3558



- A3558 – best-fit MCMC model

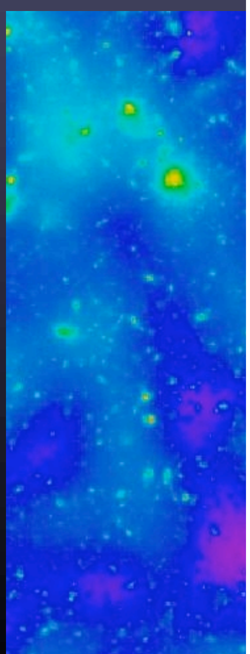
CBI SZE Interferometry Issues

- Analysis issues
  - joint CBI & Xray modelfitting
  - removal of CMB (e.g. mode projection?)
  - substructure! more sensitivity on small scales…
- GBT!
  - get GBT source measurements with new 30GHz system!
  - do SZ with GBT!
- Other SZE experiments
  - ACBAR at South Pole
  - Carlstrom's SZA and SPT
  - big bolometer arrays on GBT, ACT
  - subtract CMB by measuring at SZE null (e.g. ACBAR)

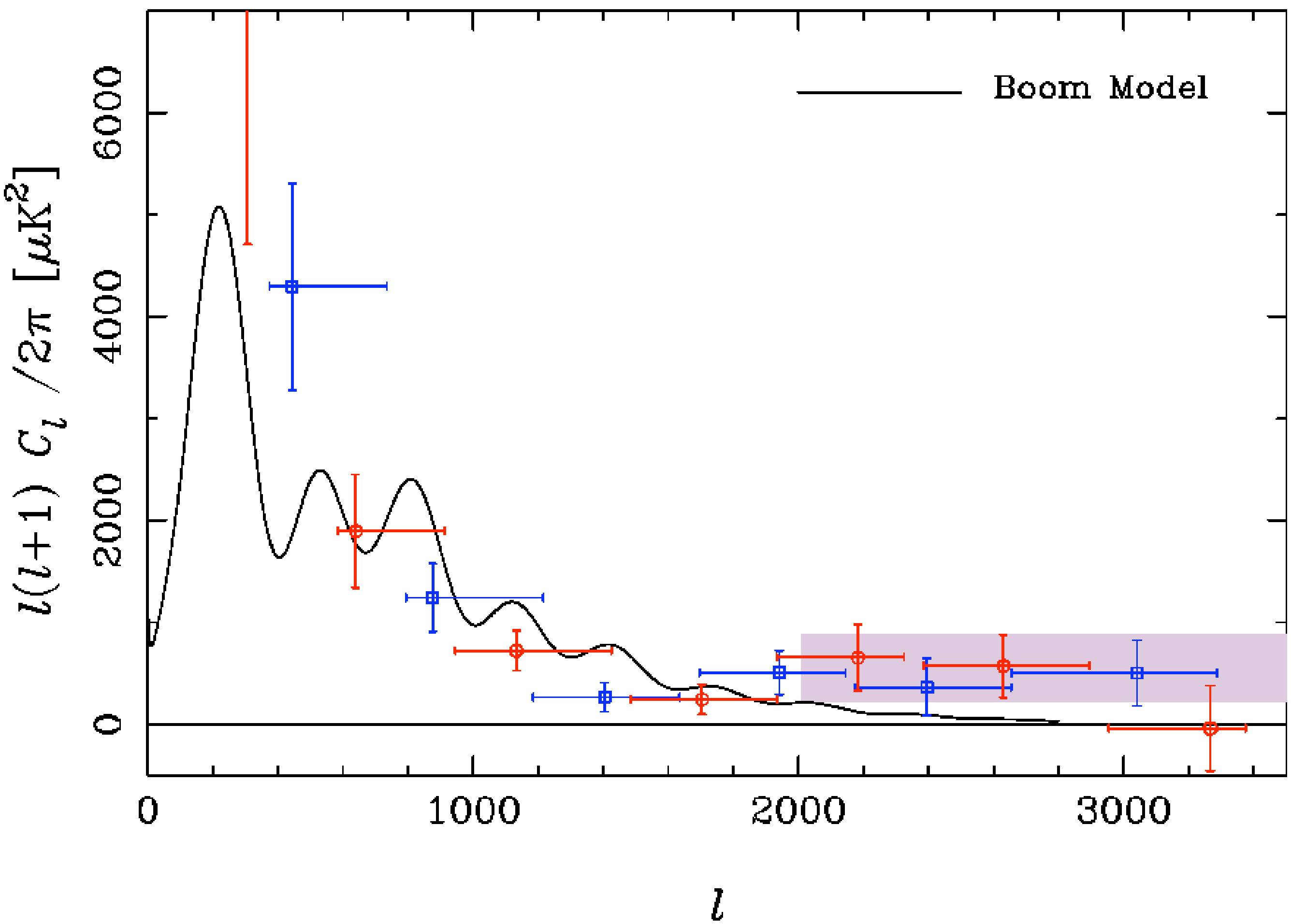
The SZE as a CMB Foreground

SZE Signatures in CMB

- Spectr
- Domin
clusters)
- Low-z
- z=1: ~
in CMB
- Ampli



Mason et al. 2003, ApJ, 591, 540



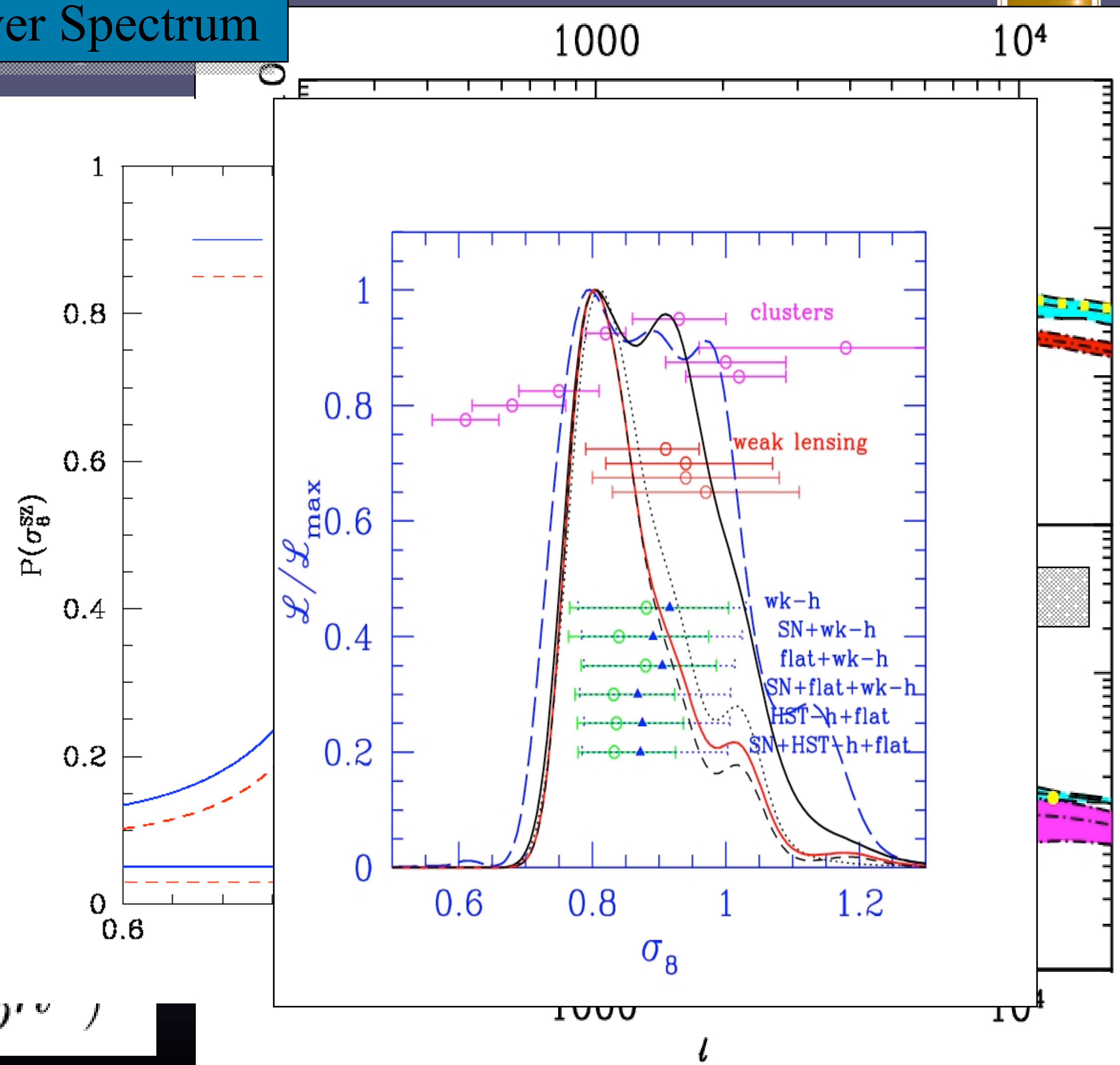
SZE Angular Power Spectrum

[Bond et al. 2002, astr

•Smooth Particle Hy
(512^3) [Wadsley et al.

•Moving Mesh Hydr
(512^3) [Pen 1998]

- •143 Mpc σ_8
- •200 Mpc σ_8
- •200 Mpc σ_8
- •400 Mpc σ_8



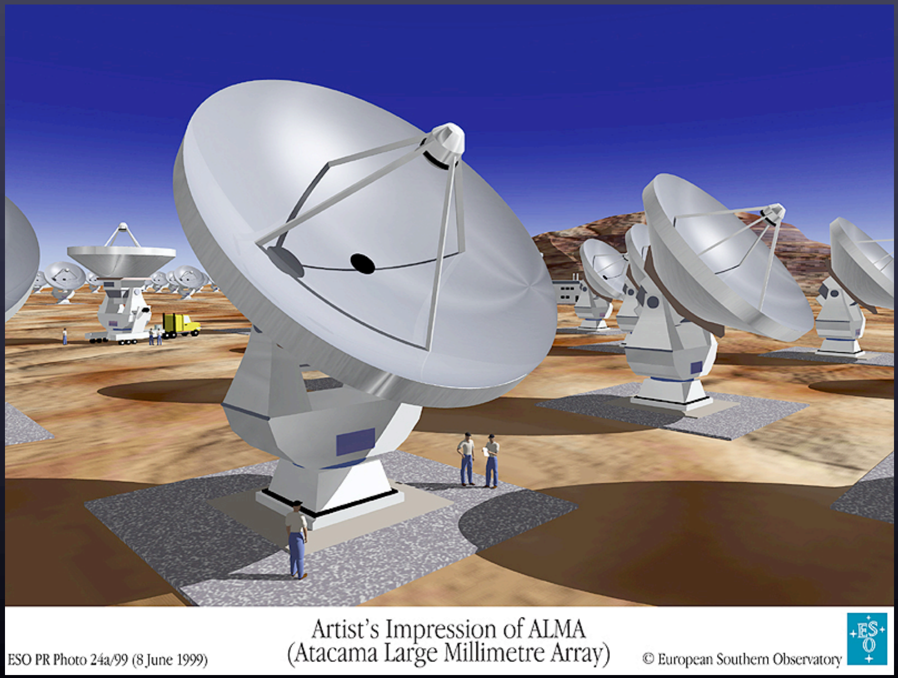
$$C_\ell^{SZ} \sim \sigma_8^7(\ldots$$

ALMA Band 1 SZE

Atacama Large Millimeter Array

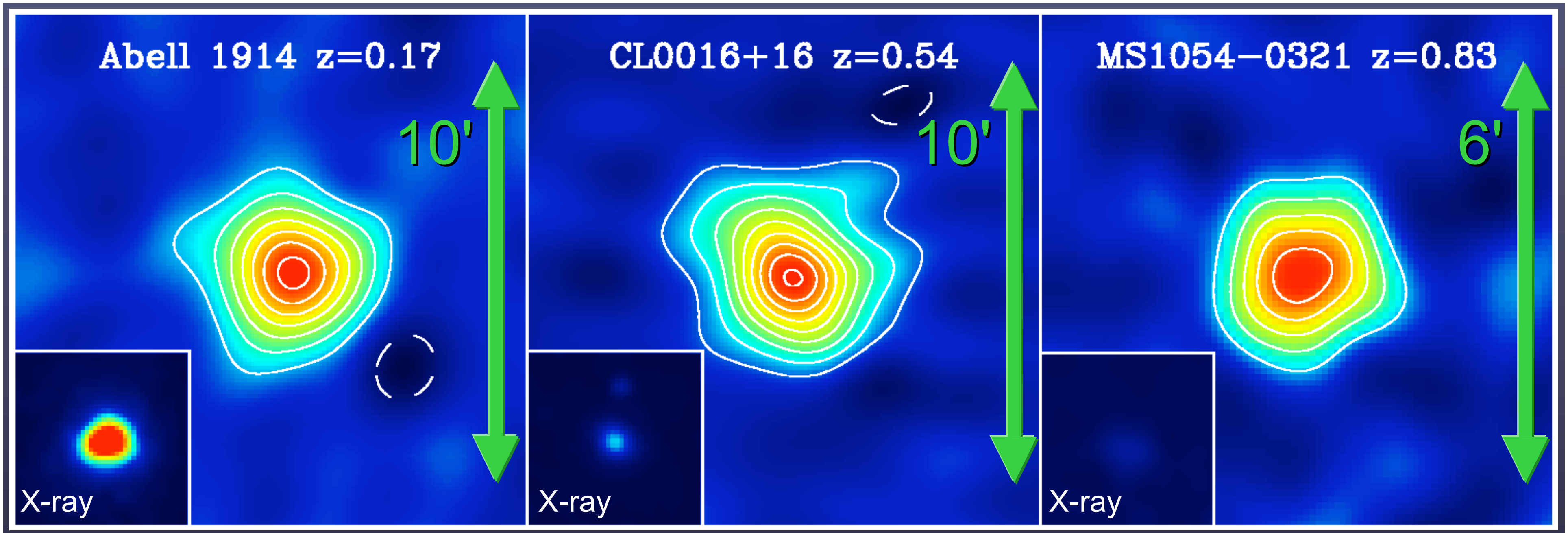
- 64 (probably 50) 12m antennas
- sub-mm grade surfaces (good to THz)
- wide-band correlator (8 GHz bandwidth)
- compact configuration (100-m)
- also ACA 10 x 7m (NAOJ)

ALMA at Chajnantor
(Courtesy NAOJ)



Artist's Impression of ALMA
(Atacama Large Millimetre Array)

The power of SZ observations



OVRO/BIMA SZE vs. X-ray (insets)

- X-ray emission brightness falls off sharply with distance
- SZE brightness independent of distance ($h\nu/kT_{cmb}$ const.)
  - only depends on profile (potential well growth) with *z*
  - can locate very distant clusters, if they exist…

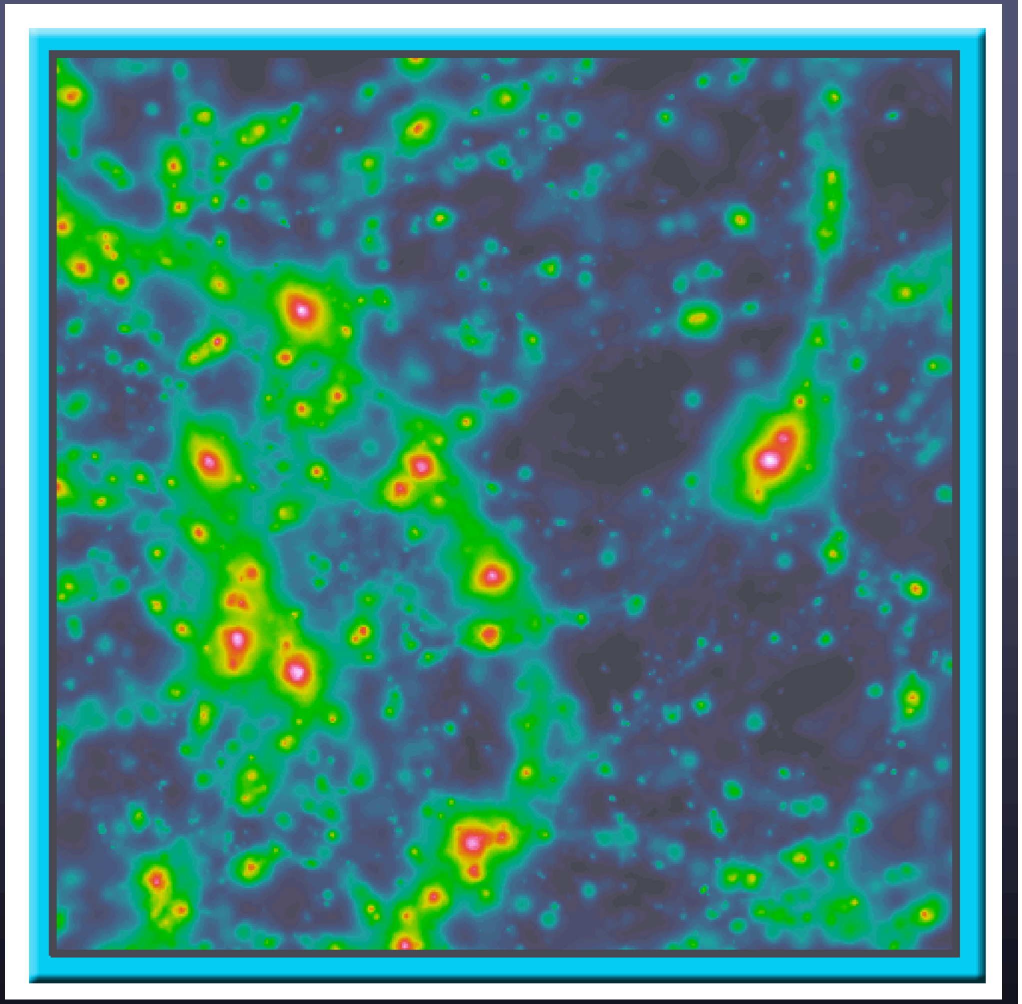
The Cosmic Web

Chart the Cosmic Web

- clusters lie at the center of the filamentary web
- hierarchy of substructure
- mergers and groups
- ALMA would study individual (sub)structures

The SZE sky

- SZE simulation (hydro)
- supercluster!



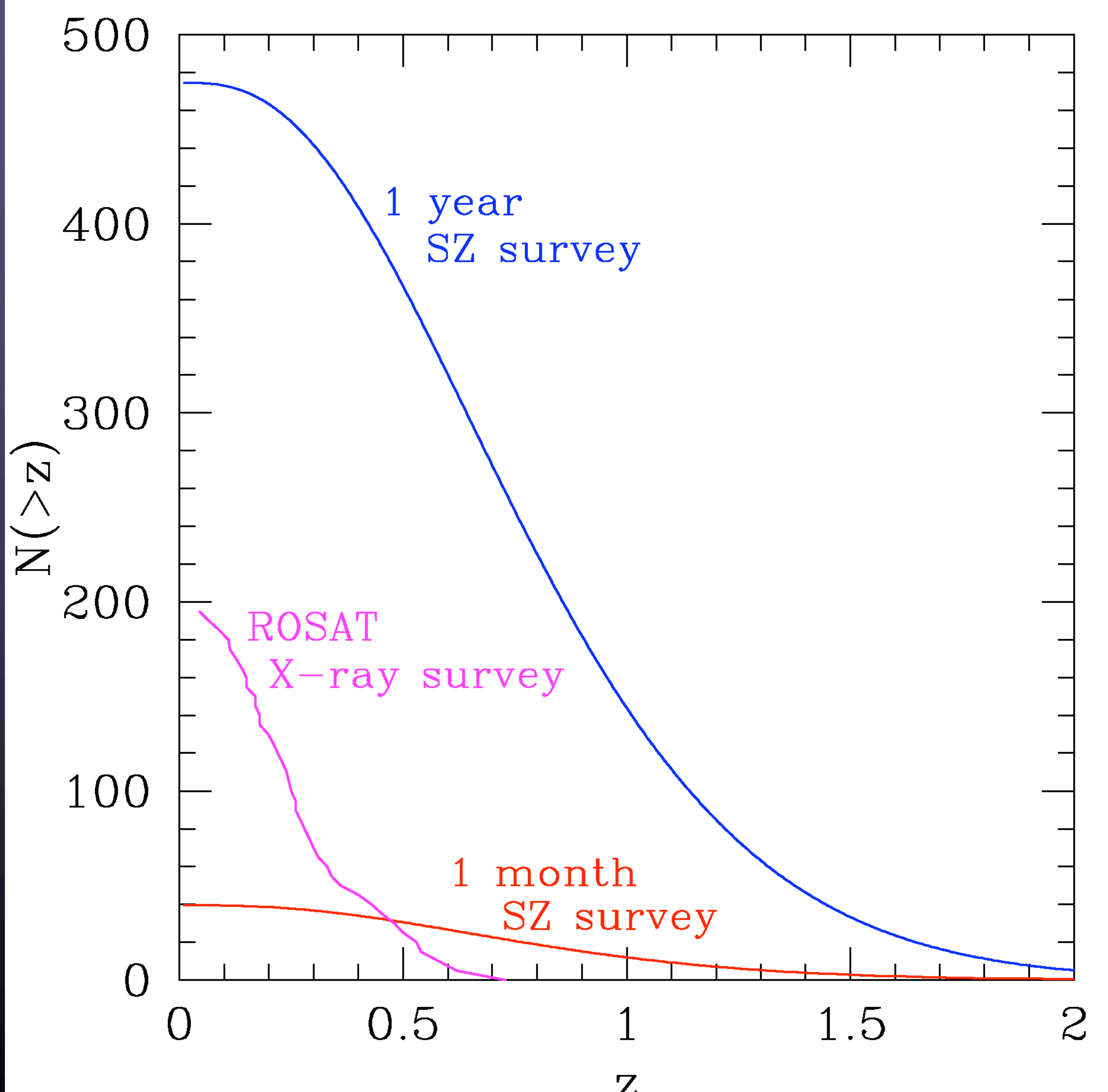
SZE Surveys: high yield!

Finding clusters

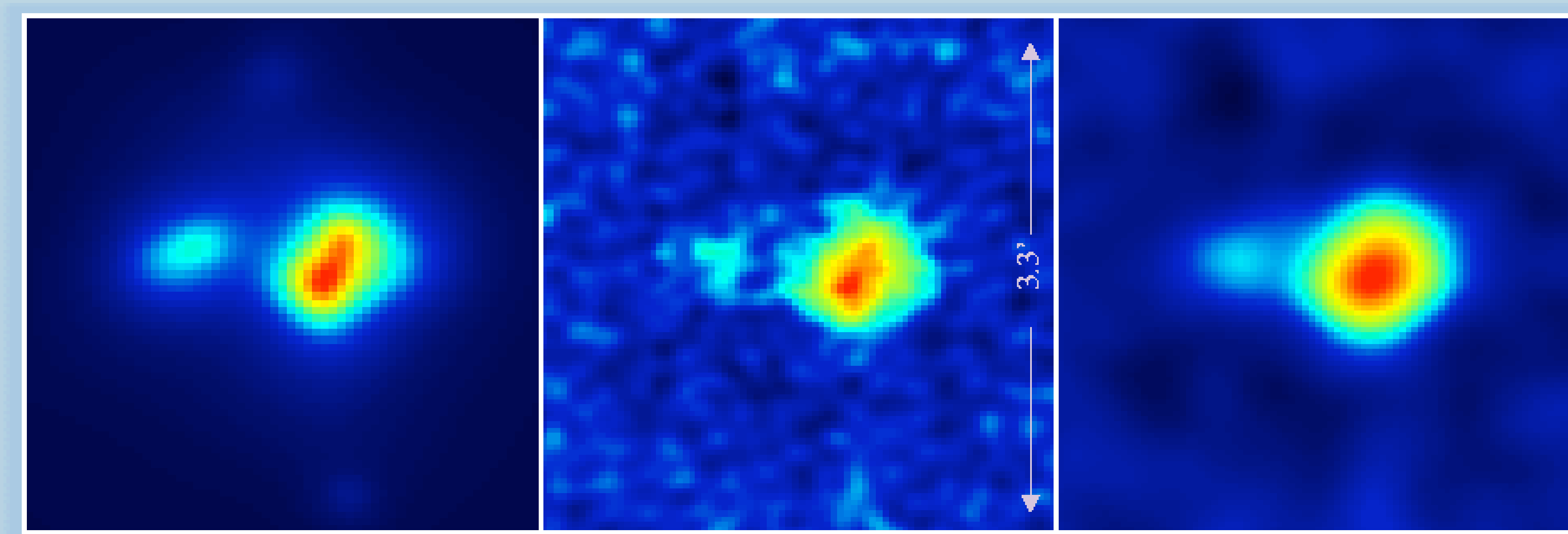
- fast instruments
- single dishes with bolometer camers
  - SPT, APEX, ACT, etc.
- or small interferometers
  - SZA, Amiba, etc.
- ALMA for follow-up!

SZ Survey

- fast bolometer array or interferometer
- e.g. SPT,APEX,SZA,AMI



Imaging the SZE with ALMA Band 1



ALMA observes SZE

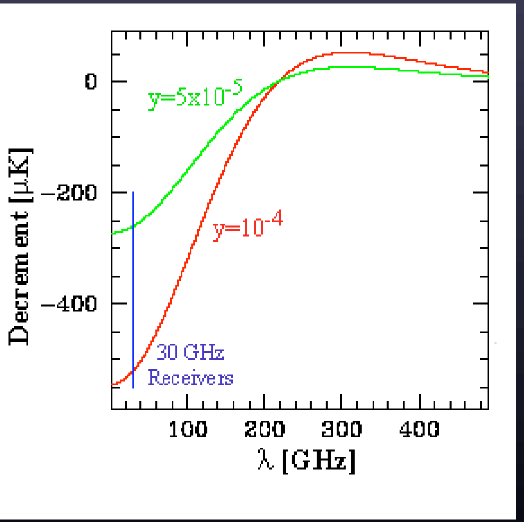
SZE simulation (left)	4 hours ALMA (center)	after 4kλ taper (right)
2.5 _ 10^{14} Msun z=1	34 GHz in compact config.	equiv. 22” FWHM
~5_ SZA survey detection	1.5 μJy (14 μK) 9.7” beam	2.8 μJy (2.7 μK)

ALMA will provide images of high redshift clusters identified in surveys from other instruments like AMI, SZA, SPT, APEX-SZ, ACT

ALMA SZ Spectral Work

- Multi-bands
  - ALMA Band 3 dish diameter ~3600λ (array 3” untapered)
- SZE spectrum
  - SZE ΔT down by 20% at 90 GHz, 50% at 150 GHz
  - allow CMB subtraction and kinetic SZE
  - want matching resolution out to SZ null (220 GHz) and beyond
  - 50m dish w/FPA (LMT) at ~200 GHz
  - **25m dish w/FPA (CCAT) at 90-150 GHz**
  - also IRAM 30m, GBT 100m with bolo arrays

ALMA is complimentary with other intruments:
A powerful global suite of telescopes
for cluster astrophysics & cosmology!



SZ Interferometry: Open questions

- Cluster Astrophysics!
  - thermal gas, non-thermal cosmic rays, magnetic fields, …
- What do realistic simulations tell us?
  - What is the level of substructure from various astrophysical sources (shocks, fronts, jets, lobes)?
  - Is an interferometer like ALMA a good way to image these?
  - Need to simulate ALMA interferometer data and reconstructed images – not just convolved images – data is in Fourier domain! May need to develop new imaging algorithms…
- Availability of complementary instruments
  - small wide-field mm/sub-mm survey telescopes (SPT, ACT, etc.)
  - big dishes + FPA (GBT, LMT, CCAT, etc.)
  - optical / IR survey telescopes (CFHT, LSST, …)
  - X-ray survey ‘scopes : **X-ray Dark Ages! Con-X too far away**

The CBI Collaboration

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